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Composite Materials and Structures Program

Rensselaer Polytechnic Institute
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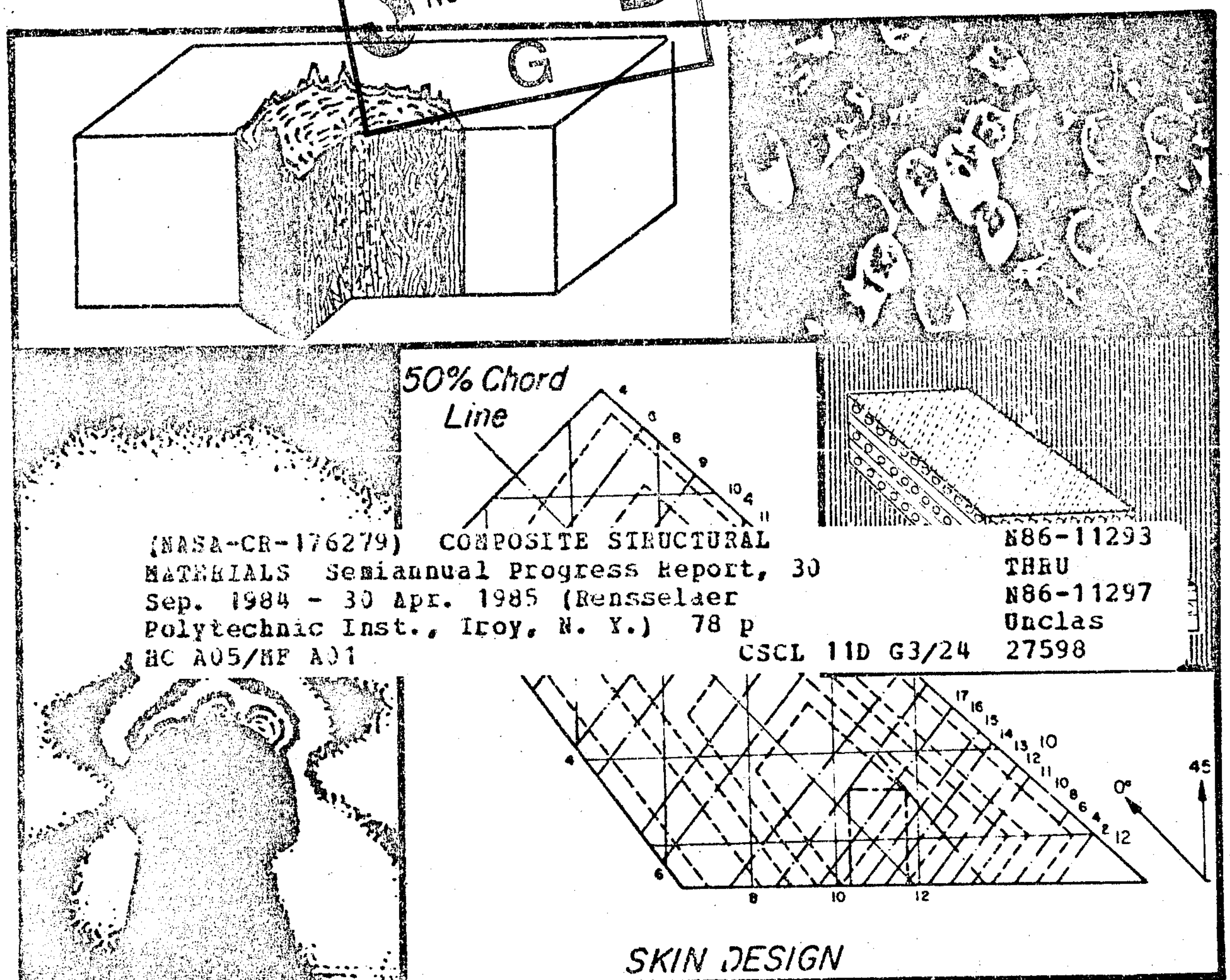

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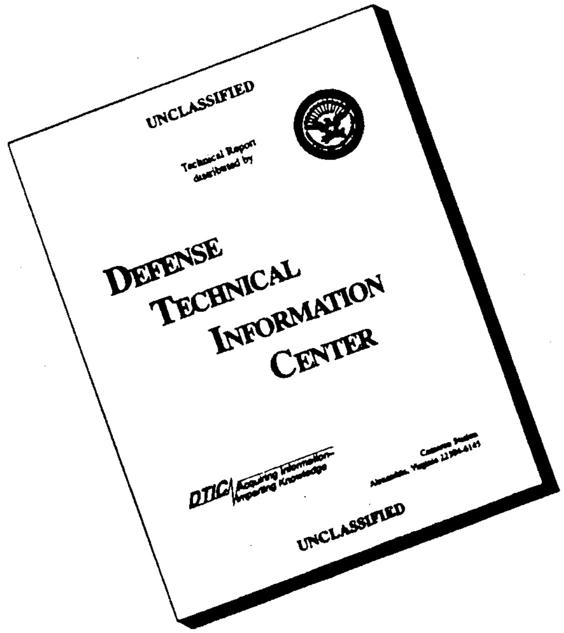

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Semi-Annual Progress Report
September 30, 1984 through April 30, 1985

COMPOSITE STRUCTURAL MATERIALS

Air Force Office of Scientific Research
and
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Grant No. NGL 33-018-003

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NASA Technical Officer

Micheal A. Greenfield
Materials and Structures Division

NASA Headquarters

48th Semi-Annual Report

August 1985

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PART I

INTRODUCTION

INTRODUCTION

A resurgence of intense interest, research and applications activity mark the beginning of what may be considered the second generation of filamentary composite materials. Such interest and activity are as well-founded now as they were at the outset of the composites era more than twenty years ago. The possibility of using relatively brittle materials with high modulus, high strength, but low density in composites with good durability and high tolerance to damage and which, when they do fail, do so in a non-catastrophic manner, has been shown feasible, and the full potential is only just beginning to be realized. The promise of substantially improved performance and potentially lower costs provides the driving force behind continued research into fiber reinforced composite materials for application in aerospace hardware. Much progress has been achieved since the initial developments in the mid 1960's. Applications to primary structure have been rather limited on operational vehicles, mainly being utilized in a material-substitution mode on military aircraft. More extensive experiments, as a part of NASA's influential ACEE program, are currently underway on large airplanes in commercial passenger operation and in a few military developments, such as the AV-8B which has seen only limited service use and the X-29 which is undergoing flight tests.

A strong technology base is required to fully exploit composites in sophisticated aerospace structures. NASA and AFOSR have supported expanding and strengthening the technology base through programs which advance fundemental knowledge and the means by which it can be successfully applied in design and manufacture.

As the technology of composite materials and structures moves toward fuller adaptation to aerospace structures, some of the problems of an earlier era are being solved, others which seemed important are being put into perspective as relatively minor, and still others unanticipated or put aside are emerging as of high priority. The purpose of the RPI program as funded by NASA and AFOSR has been to develop critical advanced technology in the areas of physical properties, structural concepts and analysis, manufacturing, reliability and life prediction.

Our approach to accomplishing these goals is through an interdisciplinary program, unusual in at least two important aspects for a university. First, the nature of the research is comprehensive. Specific projects deal with fiber and matrix constituent properties, the integration of constituents into composite materials and their characterization, the behavior of composites as they are used in generic

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structural components, their non-destructive and proof testing and, where the state of the art will be advanced by doing so, extending the research effort into simulated service use so that the composite structure's long-term integrity under conditions pertinent to such use can be assessed.

Inherent in the RPI program is the motivation which basic research into the structural aspects provides for research at the materials level, and vice versa.

Second, interactions among faculty contributing to program objectives is on a day to day basis without regard to organizational lines. These contributors are a group wider than that supported under the project. Program management is largely at the working level, and administrative, scientific and technical decisions are made, for the most part, independent of considerations normally associated with academic departments. This kind of involvement includes faculty, staff and students from chemistry, civil engineering, materials engineering, aeronautical engineering, mechanical engineering, and mechanics depending on the flow of the research.

Both of these characteristics of the NASA/AFOSR program of research in composite materials and structures foster the kinds of fundamental advances which are triggered by insights into aspects beyond the narrow confines of an individual discipline. This is often sought in many fields at a university, but seldom achieved.

A third aspect is a developing program of increased involvement between NASA's Research Center scientists and engineers in the program at RPI and vice versa. This has required, first, identification of individual researchers within NASA centers whose areas of interest, specialization and active investigation are in some way related to those of RPI faculty supported under the subject grant. Second, a program of active interchange has been encouraged and the means by which such interaction can be fostered is being sought. Important benefits envisioned from this increased communication include a clearer window to directions in academia for NASA researchers; opportunities to profit from NASA experience, expertise and facilities for the faculty so involved; and an additional channel for cross-fertilization across NASA Research Center missions through the campus program.

Overall program emphasis is on basic, long-term research in the following categories: (a) constituent materials, (b) composite materials, (c) generic structural elements, (d) processing science technology and (e) maintaining long-term structural integrity. Depending on the status of composite materials and structures research objectives, emphasis can be expected to shift, from one time period to another, among these areas. Progress in the program will be reported in the

following pages under these headings. Those computer methodology developments are also undertaken which both support Rensselaer projects in composite materials and structures research in the areas listed above and which also represent research with the potential of widely useful results in their own right.

In short, the NASA/AFOSR Composites Aircraft Program is a multi-faceted program planned and managed so that scientists and engineers in a number of pertinent disciplines at RPI will interact, both among themselves and with counterpart NASA Center researchers, to achieve its goals. Research in basic composition, characteristics and processing science of composite materials and their constituents is balanced against the mechanics, conceptual design, fabrication and testing of generic structural elements typical of aerospace vehicles so as to encourage the discovery of unusual solutions to present and future problems. In the following sections, more detailed descriptions of the progress acheived in the various component parts of this comprehensive program are presented.

PART II

CONSTITUENT MATERIALS

II-A MECHANICAL PROPERTIES OF HIGH PERFORMANCE CARBON FIBERS

II-A-1 ORDERED POLYMERS AS COMPOSITE MATRICES
II-A-2 CARBON FIBER-EPOXY INTERFACE BOND RELATED TO COMPOSITE FRACTURE
II-A-3 RESIDUAL STRESS IN HIGH MODULUS AND HIGH STRENGTH CARBON FIBERS

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II-A-1 Ordered Polymers as Composite Matrices

Senior Investigator: R. J. Dieferdorf

1. Introduction

This project is concerned with the study of polymer liquid crystals and oriented semicrystalline high-temperature thermoplastics in high modulus carbon fiber reinforced composites. It is essentially a new activity with the first real effort expended during the current reporting period. Emphasis is being placed on the determination of the effects of polymer orientation at the fiber surfaces on composite fracture and mechanical properties.

2. Progress During the Reporting Period

Examination in transmitted polarized light of polymer mesophase and melts in the presence of carbon fibers was conducted using a microscope and hot stage. The polymer mesophase did not show optical evidence of orientation at the fiber surfaces. Fiber surfaces acted as nucleating sites for spherulites in semicrystalline thermoplastics.

When an electric current was passed through carbon fibers in a cooling semicrystalline polymer melt, nucleation of crystallites took place first at fiber surfaces. Large transcrystalline regions formed along the fibers. The crystallization temperature was reduced as the voltage drop across the fibers was increased.

3. Plans for Upcoming Period

Plans for the upcoming period include making composites using a polymer liquid crystal matrix, with polymer molecules perpendicular to direction of fiber orientation. These composites will be examined to determine the effects of tensile loads on mechanical properties and on fracture behavior using a microscope tensile tester. An attempt will be made to look at the same properties in semicrystalline thermoplastics, with electro-crystallized regions at the fiber surfaces.

II-A-2 Carbon Fiber-Epoxy Interface Bond Related to Composite Fracture

Senior Investigator: R. J. Diefendorf

1. Introduction

The purpose of this study is to investigate whether the performance of carbon fiber-epoxy composites can be improved by modifying the surfaces of high modulus graphite fibers.

2. Status

Studies of the nature of the carbon fiber surface and of resin-wetting of these surfaces were completed during earlier periods and reported in previous progress reports.

3. Progress During the Reporting Period

A study was made of fracture surfaces of composites made from Aradite(R) 509 epoxy (Ciba-Geigy) with three kinds of fiber reinforcement; silicon carbide, boron and graphite. A progressive loading/examinative technique allowed step by step examination of failure progression. Composites made with silicon carbide fibers and tested to failure showed little fiber-matrix debond, and the fibers broke into short lengths. Fiber breakage appears to be the energy absorbing mechanism. In boron fiber/509 epoxy composites, extensive fracture of the matrix occurred adjacent to fibers. Debonding was seen as the mode of composite fracture in this case.

Composites made using high modulus graphite fibers had a fracture mechanism that combined fiber breakage and matrix debonding. The fiber pullout length was greater at the crack entrance than at the crack exit, regardless of the speed of crack propagation. It was concluded that a 2-t-butylaminoethanol (BAE) sizing did not significantly improve interfacial adhesion. Treatment of the fibers with hydrogen peroxide prior to applying BAE improved composite strength, and in addition imparted good lubricity to fiber surfaces.

4. Plans for Upcoming Period

Plans for the upcoming period include examining fracture surfaces of composites made from high-temperature epoxy resins, using a BAE sizing of the carbon fibers. Also, an investigation of other aminoethanol-based sizing compounds will be conducted.

II-A-3 Residual Stress in High Modulus and High Strength Carbon Fibers

Senior Investigator: R. J. Diefendorf

1. Introduction

This study concerns the investigation of residual stress in carbon fibers, and its relation to fiber mechanical properties. Calculations of residual stress from theory were carried out and comparisons with experimental measurements were made. The question of interest was whether residual stress results from processing conditions (eg. drawing), or from cool-down of the fiber? An attempt was made to explain why fiber strength decreases as fiber modulus increases.

2. Status

In previously reported studies, modulus distribution and residual stress measurements were studied for several types of PAN-based carbon fibers. Residual stress was measured by electrochemically etching off successive fiber layers, and measuring fiber contraction as a function of diameter. It was concluded that residual stress results from the skin-core morphology of high modulus PAN-based carbon fiber and results primarily from cool-down. That is, the difference in the coefficient of thermal expansion (CTE) between skin and core creates residual stress on cooling down from processing temperatures. Other factors were negligible. Residual stress appears to occur only in high modulus fibers, where the fiber core is in tension and the core tension and larger interior flaws of the high modulus fibers are seen as probably responsible for the lower fiber strength.

3. Progress During the Reporting Period

In this reporting period, theoretical calculations of residual stress were made by assuming that all stress resulted from differences in thermal contraction. The results of theoretical calculations of stress agreed very well with the results of earlier measurement.

4. Plans for Upcoming Period

This project is now considered complete.

5. Current Publications or Presentations by Professor Diefendorf on this Subject

"The Physical Chemistry of the Carbon Fiber/Epoxy Resin Interface", with C. E. Uzoh

"The Chemical Vapor Deposition in Open-Ended Capillary Tubes", with Y. Sohda

"A Theoretical Calculation of Residual Stresses in Carbon Fibers", with K. J. Chen

"The Effect of Heat Treatment on the Structure and Properties of Mesophase Precursor Carbon Fibers", with G. D. D'Abare

"The Strength Distribution of Etched Carbon Fibers", with K. J. Chen

> To be presented at the 17th Carbon Conference and published in the Proceedings of the 17th Carbon Conference, Lexington, KY, June 1985.

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PART III

COMPOSITE MATERIALS

III-A Fatigue in Composite Materials

Senior Investigator: E. Krempl

1. Introduction

The deformation and failure behavior of graphite/epoxy tubes under biaxial (axial tension and torsion) loading is being investigated. The aim of this research is to increase basic understanding of and provide design information for the biaxial response of graphite/epoxy composites.

2. Status

In Reference [1]* various phenomenological damage accumulation laws were introduced. Residual strength measurements after prior cycling at R=0 were made in tension and in combined loading. Decreases in the residual tensile and combined strength were reported as a function of prior number of cycles. In this report period the dependence of damage evolution on the degree of prior combined loadings was investigated.

3. Progress During Report Period

Combined experimental and analytical activities aimed at further development of the damage accumulation law were carried out. The multiaxial aspects and the incorporation of a fatigue limit into the equations were of special interest.

The damage evolution law previously considered is of the form

$$\frac{dD}{dN} = g(D)\ f(\phi^*) \qquad (1)$$

where D and N denote damage and cycles, respectively, and ϕ^* is an effective stress amplitude which is based on the anisotropy of the material.

The static strength in the first quadrant is well represented by

$$1 = \left(\frac{\sigma}{145}\right)^2 + \left(\frac{\tau}{233}\right)^2 \qquad (2)$$

where σ and τ are the axial and shear stress, respectively. Accordingly, the

* References in this section are given on page 17.

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effective stress amplitude ϕ^* is proposed as

$$\phi^{*2} = \left[\frac{\sigma_a}{145}\right]^2 + \left[\frac{\tau_a}{233}\right]^2 \qquad (3)$$

where σ_a and τ_a are the axial and shear stress amplitudes, respectively. The subscript a indicates values applied in a fatigue test. Fatigue tests with R=0 and a frequency of 5 Hz were then run with $\phi^* = 0.32$ and various ratios of σ_a/τ_a. The results are listed in Table III-A-1.

Table III-A-1

ϕ^*	σ_a/τ_a (degrees)*	Fatigue Life (no. of cycles)
0.322	0	11,000
0.322	30	12,000
0.322	60	12,410
0.322	75	101,410, 14,000, 39,910, 63,910
0.322	90	> 10^6

* Polar angle on the graph of τ_a vs. σ_a.

Contrary to the prediction of Equation (1) the fatigue life is not constant; thus, the anisotropy of fatigue strength is not derivable from that of the static strength.

Based on these results, Equation (1) is tentatively modified to

$$\frac{dD}{dN} = g(D)\ f(\phi^*,\alpha) \qquad (4)$$

where α is a stiffness-dependent parameter, given by

$$\alpha = \frac{A_{11}}{A_{11}^*} \qquad (5)$$

where:

$$A_{11} = \int (u_1 + u_2 \cos 2\theta + u_3 \cos 4\theta)\ dz$$

and

$$u_1 = \frac{1}{8}(3Q_{xx} + 3Q_{yy} + 2Q_{xy} + 4Q_{ss})$$

$$u_2 = \frac{1}{2}(Q_{xx} - Q_{yy})$$

$$u_3 = \frac{1}{8}(Q_{xx} + Q_{yy} - 2Q_{xy} - 4Q_{ss}) \quad .$$

The term A^*_{11} is used here as a reference stiffness, and θ is the angle between principal fiber direction and principal stress direction during fatigue testing. The step function

$$H(x) = \begin{cases} 1 & x > 1 \\ 0 & x \le 1 \end{cases} \tag{6}$$

represents the fatigue limit in Equation (5), where:

$$x = \frac{f(\phi^*, \alpha)}{f(s^*, \alpha)} \tag{7}$$

and s^* is the value of ϕ^* at the fatigue limit. With this definition, Equation (4) becomes:

$$\frac{dD}{dN} = H(x)\ g(D)\ f(\phi^*,\alpha) \ . \tag{8}$$

In principle, Equation (8) incorporates anisotropic damage accumulation properly and the fatigue limit. Specific functions valid for the $[\pm 45]_S$ Gr/E tubes are being evaluated.

4. Plans for the Upcoming Period

Experiments exploring the relations between residual strength and fatigue limit are contemplated. A critique of the specimen design made by Dr. W. Elber (NASA Langley) noted a possibly deleterious influence of interlaminar normal stresses on the strength values determined with a tubular specimen. Experiments are being planned to investigate the influence of these stresses.

5. References

[1] 46 th Semi-Annual Composite Materials and Structures Report; R.P.I., August 1984

[2] 47 th Semi-Annual Composite Materials and Structures Report; R.P.I., December 1984

6. Current Publications or Presentations by Professor Krempl on this Subject

"Time-Dependent Deformation and Fatigue Behavior of [±55] Graphite/Epoxy Tubes under Combined Loading"

Presented at the Symposium on Composites: Fatigue and Fracture, Dallas/Ft. Worth, TX, Oct 24-25, 1984.

III-B Mechanical Properties of High Performance Polymeric Matrix Composite Laminates

Senior Investigator: S. S. Sternstein

1. Introduction

This project focuses on the mechanical properties of high performance polymeric matrix composite laminates. Of specific concern are those properties of the laminate which are strongly dependent on the polymeric matrix. Previous studies in this program dealt with the viscoelastic characterization of both neat resins and composites, using dynamic mechanical spectroscopy techniques. Included in these studies were the reversible and irreversible effects of prolonged moisture interactions with epoxy based systems.

Current project goals relate to the damage tolerance of composite laminates and related phenomena, such as delamination crack propagation. Understanding is sought regarding the basic mechanisms by which laminates dissipate energy, especially when subjected to planar impact. Currently, nonlinear dissipative phenomena are being investigated in thermoplastic matrix composites. A closely related study involves the microscopic observation of failure processes in composites subjected to four point bending.

2. Status

In the previous report, cyclic hysteresis data were presented in the form of energy dissipation versus peak load or deformation for ±45 laminates subjected to uniaxial tension. In view of the highly nonlinear dependence of energy dissipation on load level, it was deemed necessary to corroborate the data by additional studies. For example, if the cyclic hysteresis energy (area inside the load-deformation loop) is truly representative of the energy loss due to multiple loading and unloading of the sample, then tests on different size samples (e.g., width and length) should give the same energy dissipation <u>per</u> <u>unit</u> <u>volume</u> of the sample. This has proved not to be the case, and therefore end effects, jaw slippage, etc are suspected.

3. Progress During Report Period

A variety of sample mounting techniques (for example, end tabs) and sample geometries have been investigated. In the course of these tests, mounting of the extensometer (used to measure sample strain independently of croschead motion) was

found to be a critical factor. It appears that the rotation of the outer plies (at 45° to the tensile axis) produces a scissor effect which can strongly alter the measured strain. This effect can literally double the measured hysteresis.

In a closely related study, the edge surface of a beam subjected to four-point bending has been observed in a miniature jig on the reflected-light microscope stage. Numerous thermoplastic matrix composites have been investigated, including polysulfone, polycarbonate, polyphenylene sulphide, PEEK and PES. All of the samples studied to date fail in the same mode, namely, the outer ply on the compression side of the beam undergoes buckling or kink-band formation. This is rapidly followed by interply and intraply delamination. Virtually no damage is observed on the tension side of the beam. It would appear that thermoplastic matrices do not offer sufficient support of the carbon fibers when the ply is in compression and has one free surface. The final result is fiber splitting and fragmentation. It seems possible that so much attention has been paid to improving damage tolerance by using tougher matrices, that the brittle character of fibers in compression has been overlooked. What is clear is that the use of more ductile matrices places new demands on the fibers, especially in compression. Clearly, it will be necessary to investigate the synergisms between matrix and fiber behavior for highly deformable matrix materials such as thermoplastics.

Bending load vs. deflection curves have also been obtained using samples with the same geometry as were used in the microscopy study. This has provided quantitative values to be compared with the buckling instability observations. These data are currently being analyzed.

4. Plans for Upcoming Period

Plans for the next reporting period include further refinements in the cyclic hysteresis measurements, particularly in relation to sample geometry, gripping and extensometer mounting. Development of a fully-reversed, cyclic bending jig is also planned. This should enable accurate measurement of hysteresis energy looses, which are strongly matrix dependent. Special emphasis will be given high load behavior and the onset of nonlinear behavior (e.g. due to yielding processes). Attempts will be made to relate these mechanical measurements to the microscopy observations of deformation phenomena at the structural level.

5. Current Publications or Presentations by Professor Sternstein on this Subject

"Mechanical Characterization of Composites"

Presented at and published in the Proceedings of the Asilomar Conference on Polymers, Asilomar, CA, Feb 11-12, 1985.

"Deformation and Failure of Thermoplastic Matrix Composites"

Presented at and published in the Proceedings of the 6th Conference on Deformation Yield & Fracture of Polymers, Cambridge, England, Apr 1-4, 1985.

"Mechanical and Optical Characterization of Thermoplastic Matrix Composites"

Presented at and published in the Proceedings of the ACS 189th National Meeting, Miami Beach, FL, Apr 28-May 3, 1985.

III-C Numerical Investigation of the Micromechanics of Composite Fracture

Senior Investigator: M. S. Shephard

1. Status

The phase of this project completed and reported at the close of the previous period marks an appropriate holding point. The project has been put on suspended status until suitable additional personnel are added. Three areas of research require additional effort to make the method of interest a practical tool for micromechanical composite fracture analysis. They are:

1) adding iterative steps after each incremental solution to control drift from the true solution,

2) developing appropriate criteria to more completely represent the fiber-matrix interfaces and

3) carrying out laboratory experiments and making the needed correlations to verify analytical solutions.

III-D Delamination in Graphite/Epoxy Laminates

Senior Investigator: T. L. Sham

1. Introduction

The purpose of this project is to attempt to understand and quantify the delamination processes in graphite/epoxy laminates using a continuum mechanics approach.

2. Status

Finite element techniques for calculating energy release rates for a crack in a homogeneous body under mixed mode loading have been implemented. The Mode I and Mode II energy release rates can be computed directly from numerical data obtained in one finite element computation using a line integral approach. The method is being extended to interfacial cracks in layered media. The line integral approach enables the energy release rate for each fracture mode to be calculated using numerical data away from the crack tip, hence improving numerical accuracy.

3. Plans for Upcoming Period

Plans for the upcoming period are to conclude the energy release rate calculations and to initiate fracture investigations in Boron/Aluminum composites.

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PART IV

GENERIC STRUCTURAL ELEMENTS

IV-A IMPROVED BEAM THEORY FOR ANISOTROPIC MATERIALS

IV-A Improved Beam Theory for Anisotropic Materials

Senior Investigator: O. Bauchau

1. Introduction

This research has concentrated on improving beam theories as applicable to composite structures. In previous progress reports analytical predictions have been presented using a new beam theory based on the assumption that cross-sections of the beam are infinitely rigid in their own plane, but free to warp out-of-plane. Experimental confirmation of these analytical predictions were sought during the current reporting period.

2. Status

The initial test specimen consisted of a low aspect ratio box beam in a cantilevered configuration. The beam specimen was fabricated by joining two graphite/epoxy panels to two aluminum C-channel webs with stainless steel fasteners. Testing of this initial beam configuration was very difficult to control, making correlation with analytical predictions nearly impossible. Furthermore, preliminary measurements revealed a local buckling phenomenon near the root attachment, which resulted in a considerable load redistribution from the lower panel to the upper one. Since the fundemental assumption in the development of the improved beam theory is that the cross-section does not deform in its own plane, large discrepancies between analytical predictions and measurements were to be expected, and were actually observed.

After identifying these deficiencies in the initial test design, a new design was implemented. First an aluminum honeycomb core was placed inside the beam so as to inhibit local buckling of the graphite/epoxy panels. The test fixture was also modified; instead of the cantilevered configuration, the beam was simply supported at both ends and loading was to be applied at midspan.

3. Progress During Report Period

Two types of specimens were manufactured that will be referred to as the "balanced" and "unbalanced" beams. In the balanced beam, both upper and lower skins of the specimen are midplane-symmetric, graphite/epoxy laminates having their axis of orthotropy aligned with the axis of the beam (the lay-up is $[\,0_2, \pm 45\,]_S$). For the unbalanced beam, the laminates still possess mid-plane symmetry, but their axis of

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orthotropy is no longer parallel to the axis of the beam (the layup is $[15_2, 30, 0]_s$). This results in laminate shear/extensional couplings, which in turn generate a bending/twisting coupling for the beam.

Each beam specimen was instrumented with strain gage rosettes on the upper panel near center span and at quarter span. Dial indicators located at center span allowed beam rotations and transverse displacements to be measured. Two loading conditions were considered; (1) a concentrated transverse shear loading at center span, and (2) a concentrated torque at center span.

The experimental results are compared with analytical predictions using various theories in Tables IV-A-1 and IV-A-2 for the balanced and unbalanced beams, respectively. Warping effect appears to be most important when modeling the torsional behavior of composite beams. The predictions of the Improved Bernoulli Solution, which accounts for warping of the cross-sections correlate well with experimental measurements in all cases.

Figure IV-A-1 shows strain distribution in the upper panel of the balanced beam and Figure IV-A-2 the corresponding strain distributions for the unbalanced beam under center torque. The Improved Bernoulli Solution is found to be in close agreement with experimental results. Warping of the cross-section of the beam results in a drastic strain redistribution, as demonstrated in Figure IV-A-1 by the large discrepancy between the Saint-Venant and Improved Bernoulli solutions. Figures IV-A-3 and IV-A-4 show the variation of the upper panel mid-width shear strain along the span of the beam. The steep shear strain variation near mid span is predicted by the Improved Bernoulli Solution and contrasts with the uniform distribution predicted by the Saint-Venant Solution.

Figure IV-A-5 shows the predicted and measured strain distributions in the upper panel of the beam under transverse loading. The measured axial and shear strains did not exhibit the shear lag effect shown in this figure to be predicted by the theory. A possible explanation for this discrepancy is the fact that the analytical model assumes a perfect shear transfer between the graphite/epoxy panels and the aluminum C-channel webs. However, testing of a beam specimen without mechanical fasteners revealed that, for the magnitude of load used in testing, shear loads were transfered through the epoxy bond at the panel/web interface rather than through the

Table IV-A-1

Comparison of Analytical and Experimental Displacements for the Balanced Beam

	Center Load Case Transverse Displacement [10^{-3} m]	Center Torque Case Rotation [10^{-3} rad]
Bernoulli Solution (no warping)	0.3072 (-15%)	0.7064 (-86%)
Improved Bernoulli Solution	0.3472 (-4%)	4.511 (-12%)
Saint-Venant Solution	0.3705 (2%)	6.500 (26%)
Experimental Results	0.3620	5.144

Table IV-A-2

Comparison of Analytical and Experimental Displacements for the Unbalanced Beam

	Center Load Case Transverse Displacement [10^{-3} m]	Center Torque Case Rotation [10^{-3} rad]
Bernoulli Solution (no warping)	0.3472 (-10%)	0.7236 (-85%)
Improved Bernoulli Solution	0.3851 (-0.6%)	4.551 (-5%)
Saint-Venant Solution	0.3950 (2%)	5.110 (7%)
Experimental Results	0.3874	4.795

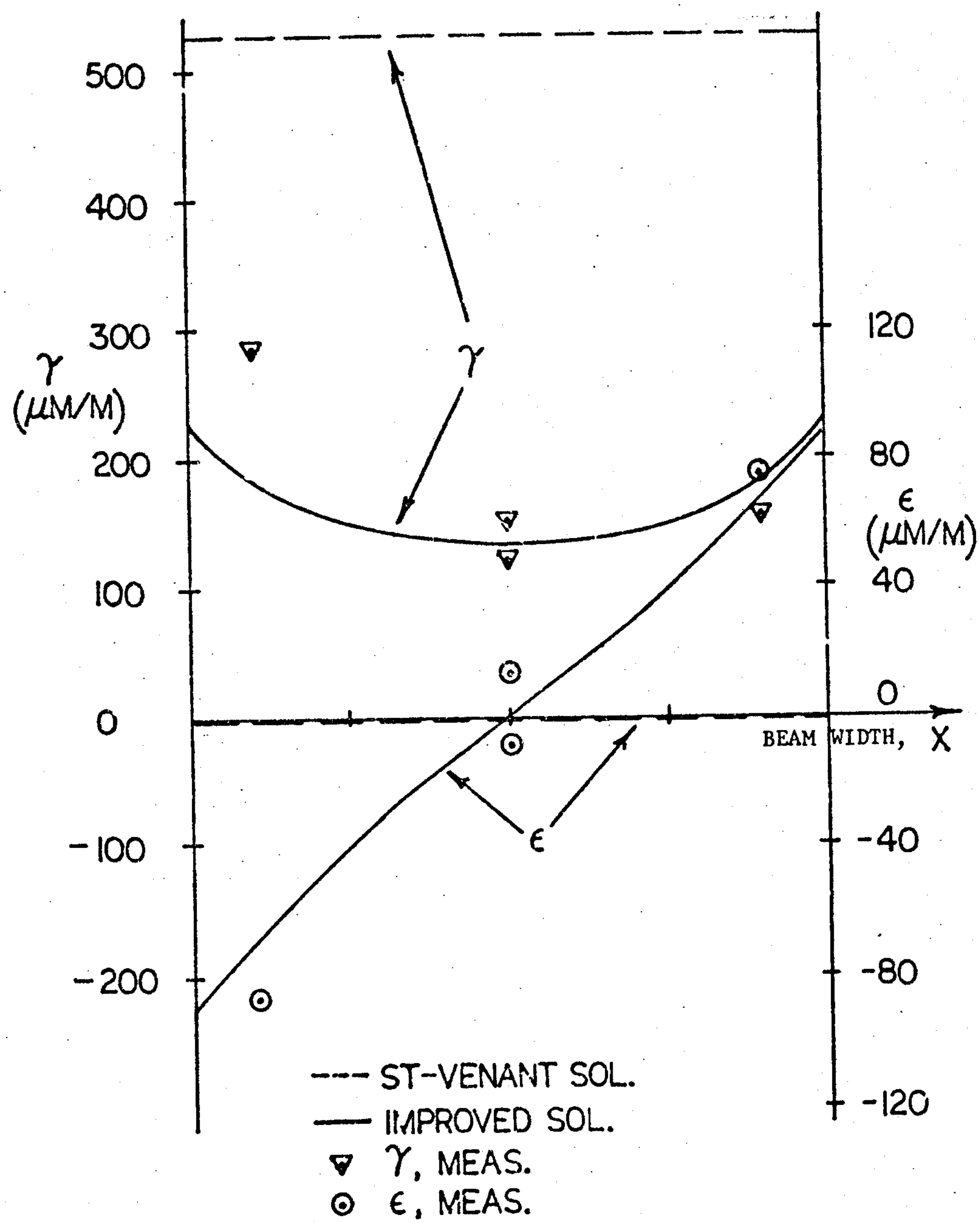

Figure IV-A-1. **Strain Distributions Across the Beam Width, Near Center Span ($z/L = 0.45$), in the Upper Panel of the Balanced Beam Under 54.5 Newton-Meter Center Torque.**

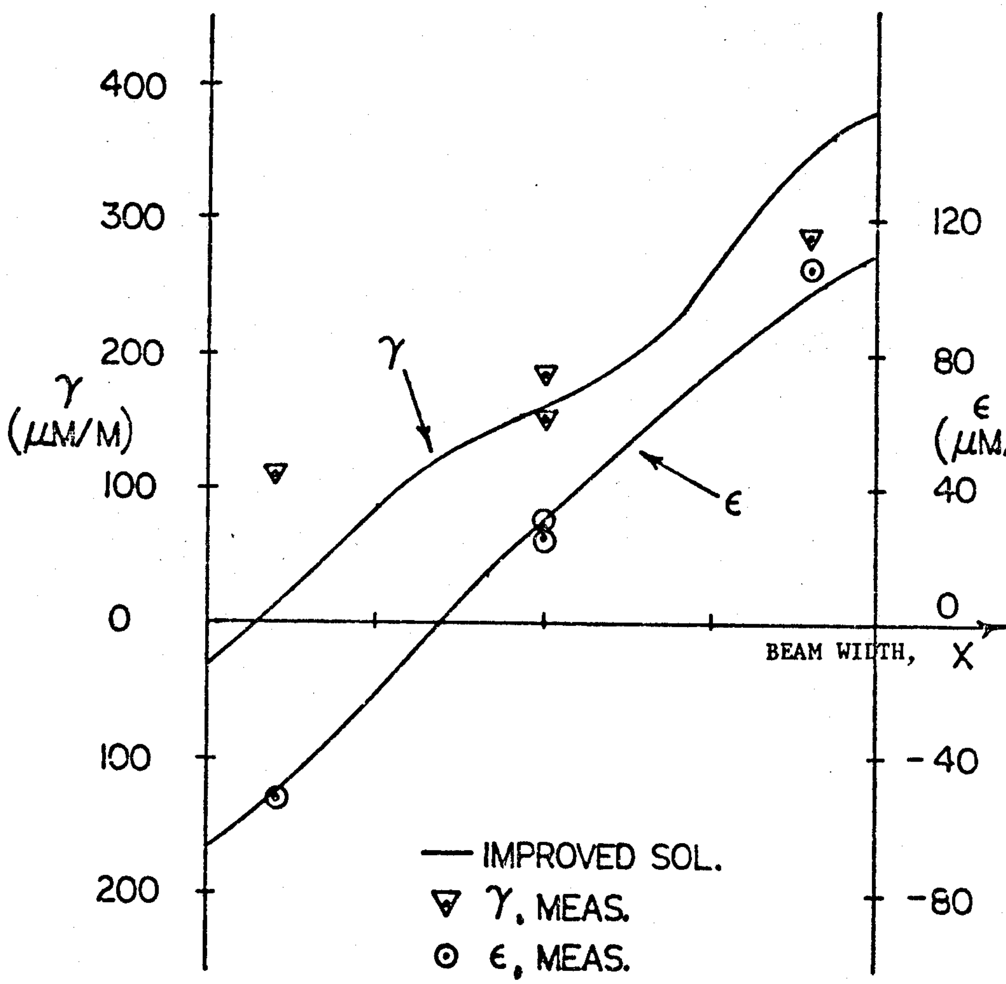

Figure IV-A-2. Strain Distributions Across the Beam Width, Near Center Span (z/L = 0.45), in the Upper Panel of the Unbalanced Beam Under 54.5 Newton-Meter Center Torque.

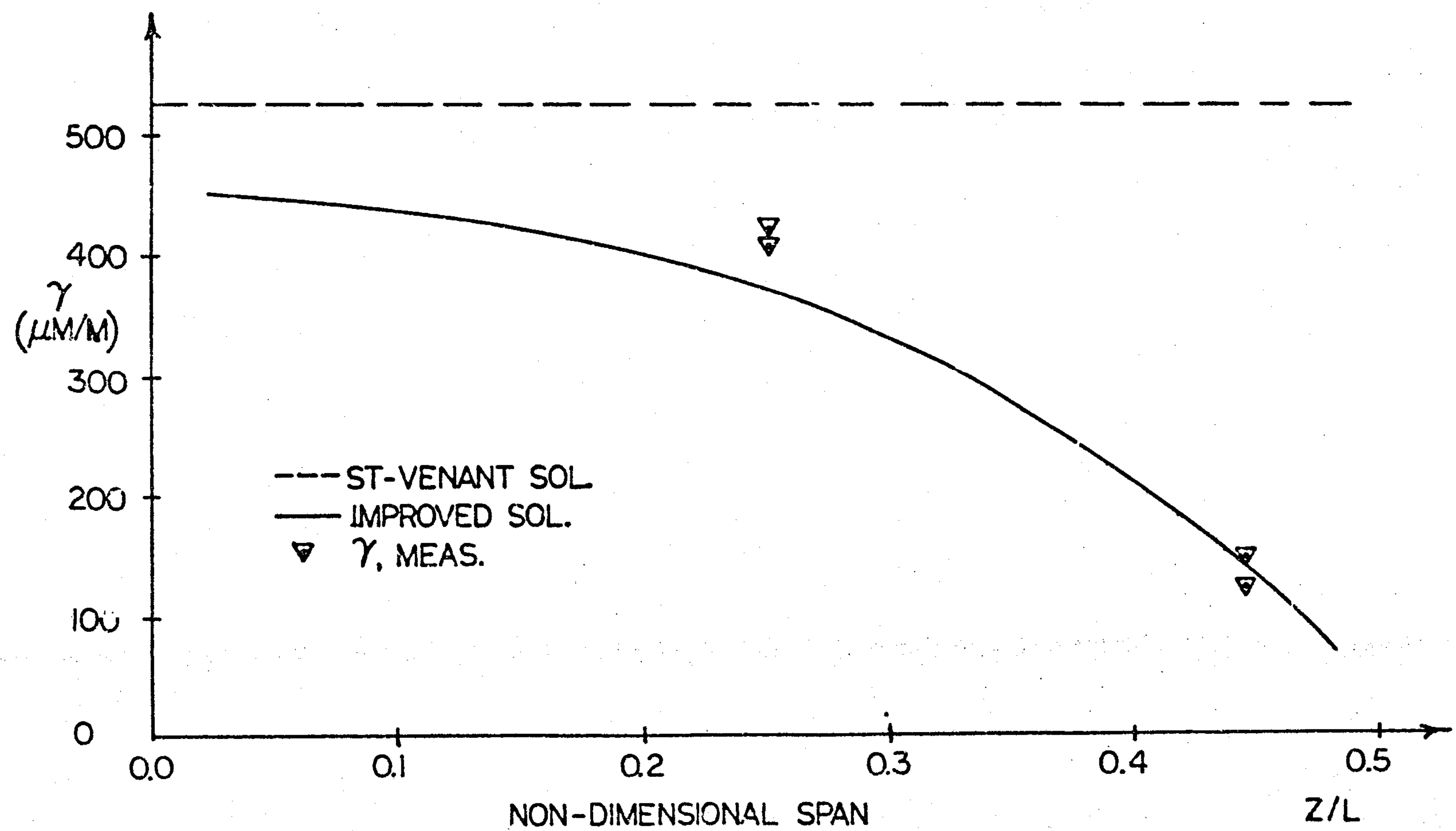

Figure IV-A-3. Balanced Beam - Upper Panel Mid-Width Strain Under a 54.5 Newton-Meter Center Torque.

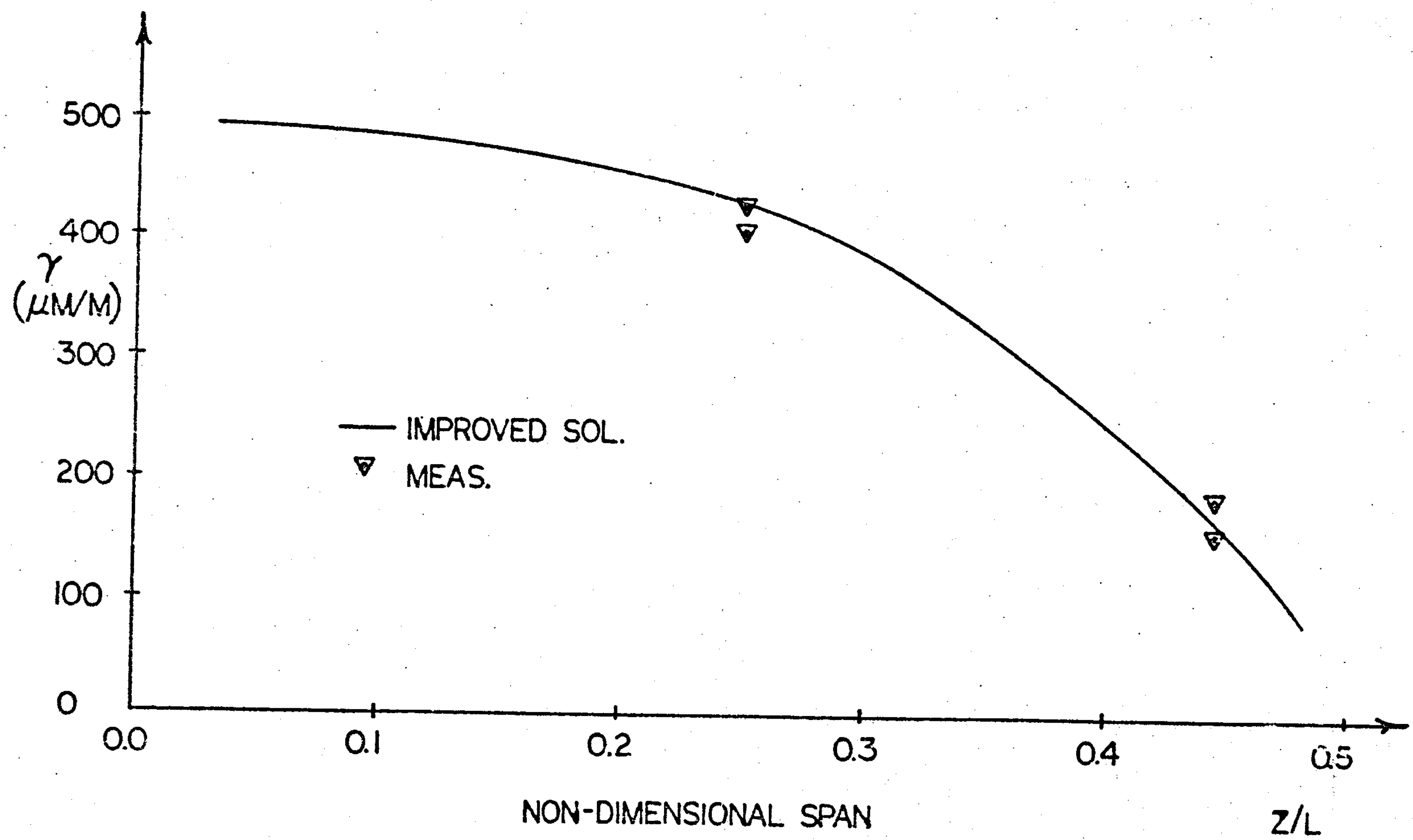

Figure IV-A-4. Unbalanced Beam - Upper Panel Mid-Width Strain Under a 54.5 Newton-Meter Center Torque.

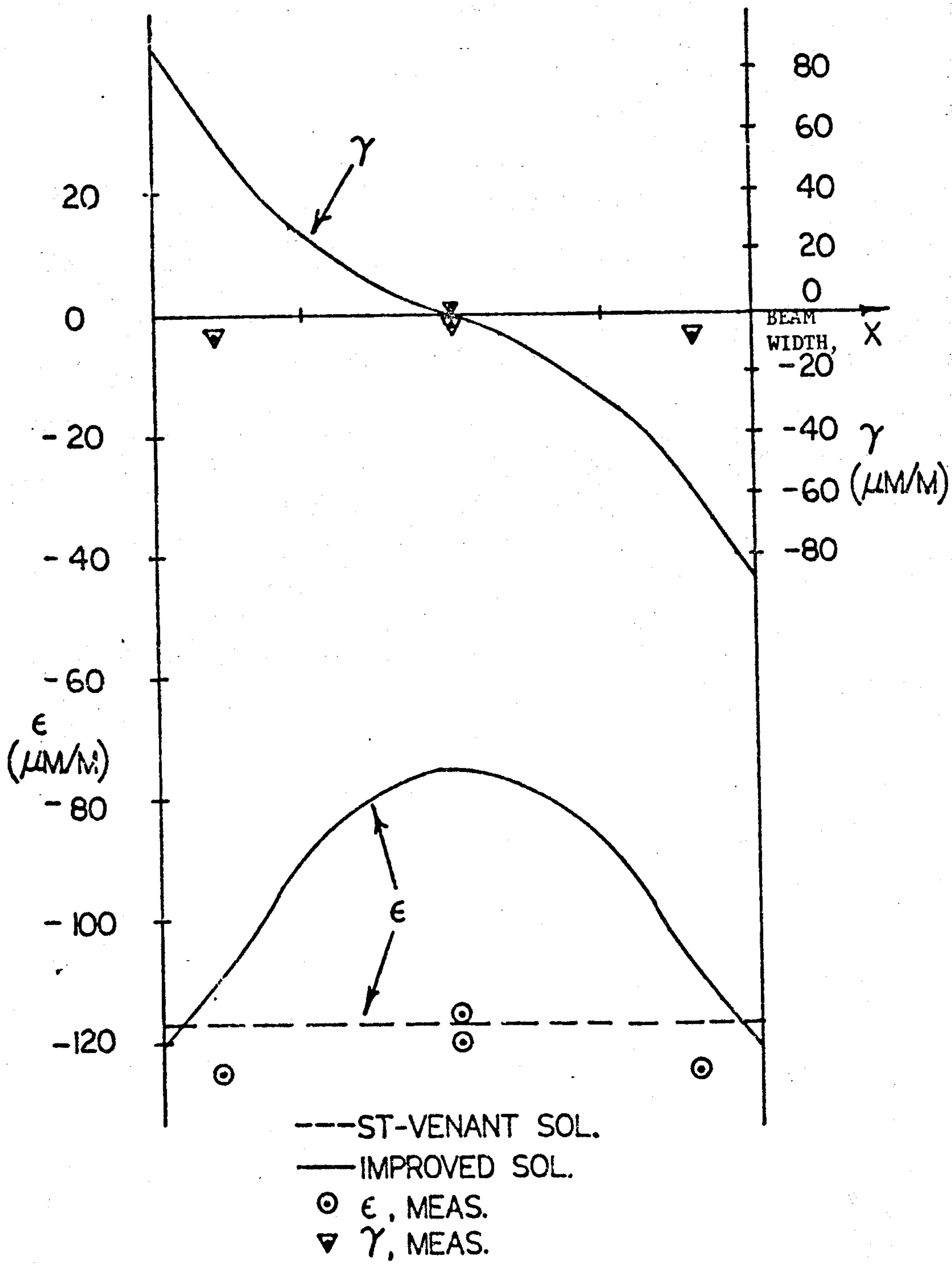

Figure IV-A-5. Strain Distributions Across the Beam Width, Near Center Span (z/L = 0.45), in the Upper Panel of the Balanced Beam Under 500 Newton Center Load.

fasteners. This imperfect shear transfer probably accounts for the observed discrepancy.

4. Plans for Upcoming Period

As mentioned above, specimens without a honeycomb core were tested in early stages of the experiments. Detailed strain measurements showed that one of the panels of the beam was undergoing out-of-plane bending deformations, typical of buckling behavior. This behavior results in deformations of cross-sections in their own plane and cannot be modeled within the frame of a warping theory that specifically assumes sections which are infinitely rigid in-plane. Accordingly, in the upcoming period, research will concentrate on the development of a general beam theory for thin-walled structures, that includes cross-section deformations. Both numerical and experimental aspects will be addressed. This research will focus; (1) on a better understanding of the mechanics of thin-walled structures, and (2) on applications to typical aeronautical structures such as stiffened wing or fuselage components.

5. Current Publications or Presentations by Professor Bauchau on this Subject

"A Beam Theory for Anisotropic Materials"

To be published in the Journal of Applied Mechanics, Vol. 52, No. 2, pp. 416-422, June 1985.

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PART V

PROCESSING SCIENCE AND TECHNOLOGY

V-A Thermal Analysis of Composite Materials

Senior Investigator: B. Wunderlich

1. Introduction

This is the fourth report in an effort to analyze the thermal properties of composites. All glassy materials commonly used in the aerospace industry were considered initially. To achievo sufficient precision, the calorimetric measuring method [1]* was improved. Preliminary results on glass transition changes, broadening and changes in magnitude were presented in Reference [2]. A comprehensive summary of these data will be available in a graduate thesis and excerpts will be available as Reference [3], in Fall 1985. The present report shows a change toward more fundamental work in this area of thermal analysis of composites. It was observed that only more precise analysis of the solid state can provide the detailed information desired. Further, better understanding seemed more likely if a wider range of material properties (e.g., other than just epoxies) are analyzed. This broadening of approach will become clear in this report. A fuller summary of the last two year's progress is given in Reference [4], which covers all research carried out under the direction of the senior investigator.

2. Status

At the beginning of the previous report period it was established that the well-known increase in glass transition temperature, Tg, also contains information on the uniformity of cure through the broadness analysis of the transition. This led to including compounds with chemical structures of importance in cross-linked, high-temperature polymers in our heat capacity analysis ($-C_6H_4-$) using approximate vibrational spectra.

3. Progress During Report Period

a. The Heat Capacity of Solid Poly-p-xylylene and Polystyrene

The heat capacity at constant pressure, Cp, of poly-p-xylylene (PPX) has been measured from 220 to 625 °K using differential scanning calorimetry. The heat capacities at constant volume, Cv, of both PPX and its isomer polystyrene (PS) have

* References in this section are given on page 42.

been interpreted using literature data on full normal mode calculations for PS and estimates from ˙ ʻ molecular weight analogues for PPX for the 39 group vibrations. Nine skeletal ʼn· ˈi· ıs were used with Θ_1 and Θ_3 temperatures of 534.5 °K and 43.1 °K for PS. It was also possible to calculate a heat capacity contribution of a phenylene group within a polymer chain. Single 48-vibration Θ_1 temperatures of 3230 °K for PS and 2960 °K for PPX are sufficient to describe Cv above 220 °K. Below 140 °K, PS heat capacity shows deviations from the Tarasov treatment.

b. Quantitative Thermal Analysis of Macromolecular Glasses and Crystals

Quantitative thermal analysis means scanning calorimetry. Today a precision of ±1% or better can be achieved over the enormous temperature range from 100 °K to 1000 °K. Since scanning calorimetry is fast, it is also possible to study metastable systems as are encountered in macromolecules. Most macromolecular systems are only partially or not at all crystallized, i.e., they are partially or fully glassy. By establishing the fully-crystalline and fully-glassy, limiting thermal properties, a detailed determination of the common intermediate states was possible. A series of 10 polyoxides and polyolefins were considered for which all thermal properties are known from 0 °K to beginning decomposition in the melt. The glass transitions of semicrystalline polymers were given special attention since they are indicative of a wide variety of structure-sensitive effects.

4. Plans for Upcoming Period

In the upcoming period our work will be an effort to identify the glass transition and the melting transition more precisely for polymers which are also under investigation mechanically. Polycarbonates, polyoxides, polysulfides and peek (poly ether ether ketone) will be analyzed relative to their thermodynamic properties by measurement of heat capacity and vibrational analysis of the solid state, as outlined for polystyrene and PPX, above. Analysis of liquid and condis crystals will also be continued.

5. References

[1] 46 th Semi-Annual Composite Materials and Structures Report; R.P.I., August 1984

[2] 47 th Semi-Annual Composite Materials and Structures Report; R.P.I., December 1984

[3] 49 th Semi-Annual Composite Materials and Structures Report; R.P.I., to be published.

[4] 3 rd ATHAS Report - 1985; R.P.I., February 1985

6. Current Publications or Presentations by Professor Wunderlich on this Subject

"Precision Heat Capacity Measurements for the Characterization of Two-Phase Polymers"

Presented as the Plenary Lecture at the Italian Association for Thermal Analysis and Calorimetry Meeting, Naples, Italy, Dec 4-7, 1984.

"The Kinetics of Molecular Nucleation", with Dr. S. Cheng and

"Thermal Analysis of the Condis Crystals of Poly-p-xylylene"

Presented at the American Physical Society Meeting, Baltimore, MD, Mar 25-29, 1985.

"Thermal Analysis of Liquid and Condis Crystals"

Presented as the Invited Plenary Lecture at the ACS 189th National Meeting, Miami Beach, FL, Apr 28-03 May, 1985.

"Quantitative Thermal Analysis of Macro-Molecular Glasses"

To be published in Thermochemica Acta, Vol. 92, pp. 15-26, Sept. 1985.

"Heat Capacity of Solid Poly-p-xylylene and Poly-styrene", with D. Kirkpatric and L. Judovits

To be published in the Journal of Polymer Science and Polymer Physics Edition, 1985.

V-B Numerical Analysis of Composite Materials

Senior Investigator: M. S. Shephard

1. Introduction

The complexities associated with composite materials as regards both design and manufacture demand the use of electronic computation to efficiently utilize these materials. Presently, the analyses performed in connection with a new part are related primarily to proper design for their use in service. The goal of this new project is to develop the appropriate analysis tools needed to describe the processing of continuous fiber resin matrix composites.

Composite properties are directly related to the quality of the laminate that results from the fabrication process. This manufacturing process is a very complex operation that depends on many variables. Better understanding of such processes will improve control of the manufacturing variables and result in more desirable qualities in the finished product. The differential equations that describe composite processing are, as might be expected, very difficult. Numerical analysis provides a means for their solution. The approach taken in this project combines numerical solution of the governing equations with incorporation of proper input data and comparison with experimental results.

2. Status

The matrix systems that are of interest for this work include both thermosetting and thermoplastic resins. Processing steps take on slightly different general forms for each of these types of matrices. There is a considerable overlap in the types of numerical analyses, however, that are required to understand the curing of thermoset and the processing of thermoplastic composites. The primary processes that must be considered in the analysis of both classes of composites were outlined in the previous progress report. Initial investigations are concentrated on qualifying the governing partial differential equation (and/or variational principles) in a form to which numerical analysis, via finite element techniques, can be applied. A second, equally important, criterion is that appropriate coefficients required for the analysis can be obtained from experimental results. Efforts to date indicate that there will be some difficulties obtaining the needed material parameters in the desired form, particularly for flow related parameters of thermoplastic resin. This situation will require special consideration and may necessitate modification of the governing equations used.

The procedures developed to date have concentrated on problems described in one spatial dimension, which is then discretized into finite elements. Since the finite element procedures used are general, moving to two- and three-dimensional domains will not require the restructuring of the analysis software developed. It will, however, require the inclusion of additional behavioral phenomenon which are introduced with the increase in dimensionality.

3. Progress During Report Period

The analysis capabilities developed in the current period are concerned with a solution to a form of the general macroscopic energy equation which neglects kinetic energy and is applicable to both thermosets and thermoplastics. This equation is:

$$\rho_c \frac{D(C_c T)}{Dt} = \nabla [K_c] \nabla T + \dot{Q}(T,t)$$

where:

ρ_c = mass density of the composite

t = time

T = temperature

C_c = heat capacity of the composite

$\dot{Q}$ = rate of heat energy release due to all internal sources or sinks

$[K_c]$ = thermal conductivity matrix

and, for a cartesian coordinate system,

$$\frac{D(\;)}{Dt} = \frac{\partial(\;)}{\partial t} + u\frac{\partial(\;)}{\partial x} + v\frac{\partial(\;)}{\partial y} + w\frac{\partial(\;)}{\partial z}$$

$$\nabla = \left[\; \frac{\partial}{\partial x} \quad \frac{\partial}{\partial y} \quad \frac{\partial}{\partial z} \;\right]$$

so that, for example,

$$\nabla T = \left[\; \frac{\partial T}{\partial x} \quad \frac{\partial T}{\partial y} \quad \frac{\partial T}{\partial z} \;\right]$$

The current analysis is concerned with a thermoset, where the assumptions applied to the energy equation are that resin flow has been completed before the reaction

begins and that heat is transfered only in the Z-direction. Under these restrictions, the energy equation can be written as

$$\rho_c C_c \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left(K_c \frac{\partial T}{\partial z} \right) + \rho_m H_R \frac{\partial \alpha}{\partial t}$$

where

ρ_c, ρ_m = mass densities of the composite and matrix, respectively

H_R = total heat of reaction

$\frac{\partial \alpha}{\partial t} = \dot{\alpha}$ = the rate of reaction

Numerical solution of this equation was obtained using finite elements in the spatial domain and finite differences in the temporal domain. The application of the finite element spatial discretization reduces the P.D.E. in space and time to a first order, matrix O.D.E. which can be written as

$$[\, M \,] = \frac{\partial \{ T \}}{\partial t} + [\, K \,] \{ T \} - \{ F \} = 0 \qquad (1)$$

where

$$[\, M \,] = \sum_{elem} \int_{z_{i-1}}^{z_i} \rho_c C_c \begin{bmatrix} N_{i-1}^2 & (N_{i-1} N_i) \\ (N_{i-1} N_i) & N_i^2 \end{bmatrix} dz$$

$$[\, K \,] = \sum_{elem} \int_{z_{i-1}}^{z_i} K_c \begin{bmatrix} N_{i-1,z}^2 & (N_{i-1,z} N_{i,z}) \\ (N_{i-1,z} N_{i,z}) & N_{i,z}^2 \end{bmatrix} dz$$

$$[\, F \,] = \sum_{elem} \int_{z_{i-1}}^{z_i} \rho_m \begin{bmatrix} N_{i-1}^2 & (N_{i-1} N_i) \\ (N_{i-1} N_i) & N_i^2 \end{bmatrix} \begin{Bmatrix} \dot{\alpha}_{i-1} \\ \dot{\alpha}_i \end{Bmatrix} dz$$

$\{ T \}$ = a set of nodal temperatures which represent the unknown to be solved for.

In these studies, piecewise-linear finite element shape functions, N_i, were used. The matrix O.D.E. was solved using a backward difference scheme, which was selected for stability reasons. Assuming the use of equal time steps, Δt, the backward difference relationship used to approximate the time derivative was

$$\left.\frac{\partial\{T\}}{\partial t}\right|_n \approx \frac{\{T\}_n - \{T\}_{n-1}}{\Delta t} = \{T'\}_n$$

Substituting this expression into Equation (1) and solving for $\{T\}_n$ yielded

$$\{T\}_n = \left[\frac{[M]}{\Delta t} + K \right]_n^{-1} \left\{ \left[\frac{[M]}{\Delta t}\right]_n \{T\}_{n-1} + \{F\}_n \right\} \tag{2}$$

Since the terms on the RHS of Equation (2) are a function of T and α, an iterative method must be used to solve each time step. A simple secant method was used.

To demonstrate the capabilities developed to date and indicate the importance of boundary condition specification, two example problems were considered. Both use the same material, consisting of graphite fibers in a polyester matrix. The chemical properties of the polyester [1]* were taken as

$H_R = 73$ cal/g

$\frac{d\alpha}{dt} = (1-\alpha)\, Ae^{-C/RT}$

$A = 2.39 \times 10^{10}\ \left(\frac{1}{\text{min}}\right)$

$C = 18700$ cal/mol

The material properties used for the fibers [2] and matrix are

graphite fibers	polyester matrix
$\rho_f = 1.79 \times 10^3$ Kg/m^2	$\rho_m = 1.26 \times 10^3$ Kg/m^2
$C_f = 0.712$ KJ/(kg °K)	$C_m = 1.26$ KJ/(kg °K)
$K_f = 26$ W/(m °K)	$K_m = 0.167$ W/(m °K)

The material properties for the composite were obtained by applying the rule of mixtures [3,4] to the constituents. Assuming a 60% volume fraction for the fibers

* References in this section are given on page 56.

yielded

$$\rho_c = 1.56 \times 10^3 \ \ Kg/m^2$$

$$C_c = 0.9312 \ KJ/(kg \ °K)$$

$$K_c = 0.413 \ W/(m \ °K)$$

In the first example, a Dirichlet boundary condition was applied to both the top and bottom surface. These are also the form of boundary conditions applied in previously published work [2]. Assuming a value of T = 354 °K on both top and bottom of a 0.764 cm composite layup, the results shown in Figure V-B-1 and V-B-2 were obtained. Figure V-B-1 shows the temperature distribution through the composite at four time intervals in the process, while Figure V-B-2 shows the degree of cure completion through the thickness at two of the later time intervals. The application of the Dirichlet boundary conditions implies large heat sinks at the two surfaces which extract the heat generated by the chemical reaction as quickly as it can be conducted to the surfaces. The results presented do not appear realistic since the heat is being extracted so rapidly as to retard the rate of reaction (which increases with temperature).

In the second example, a Neumann type free convection boundary condition is used. In particular, a free convection coefficient, h, of 2 $W/(m^2 \ °K)$ was used with the ramped air temperature profile shown in Figure V-B-3. Figure V-B-4 shows the temperature profile thirty minutes into the cure. At this point the chemical reaction has not been activated and the dip in the curve is caused by the lag time due to conduction through the composite. Figure V-B-5 shows the temperature distribution just one minute later. At this point the reaction has taken off and the composite temperature has risen from a level more than 30° below the air temperature to a level about 8° above the air temperature. Figure V-B-6 shows the temperature just 30 seconds later, at which time the composite temperature has risen to over 580 °K which is neary 200° above the air temperature.

The above examples demonstrate the difference in results that will be obtained for a particular material depending on the boundary conditions used. The boundary conditions used in the examples represent two extreme cases. The modeling of more appropriate boundary conditions is one of the major problem areas that must be addressed.

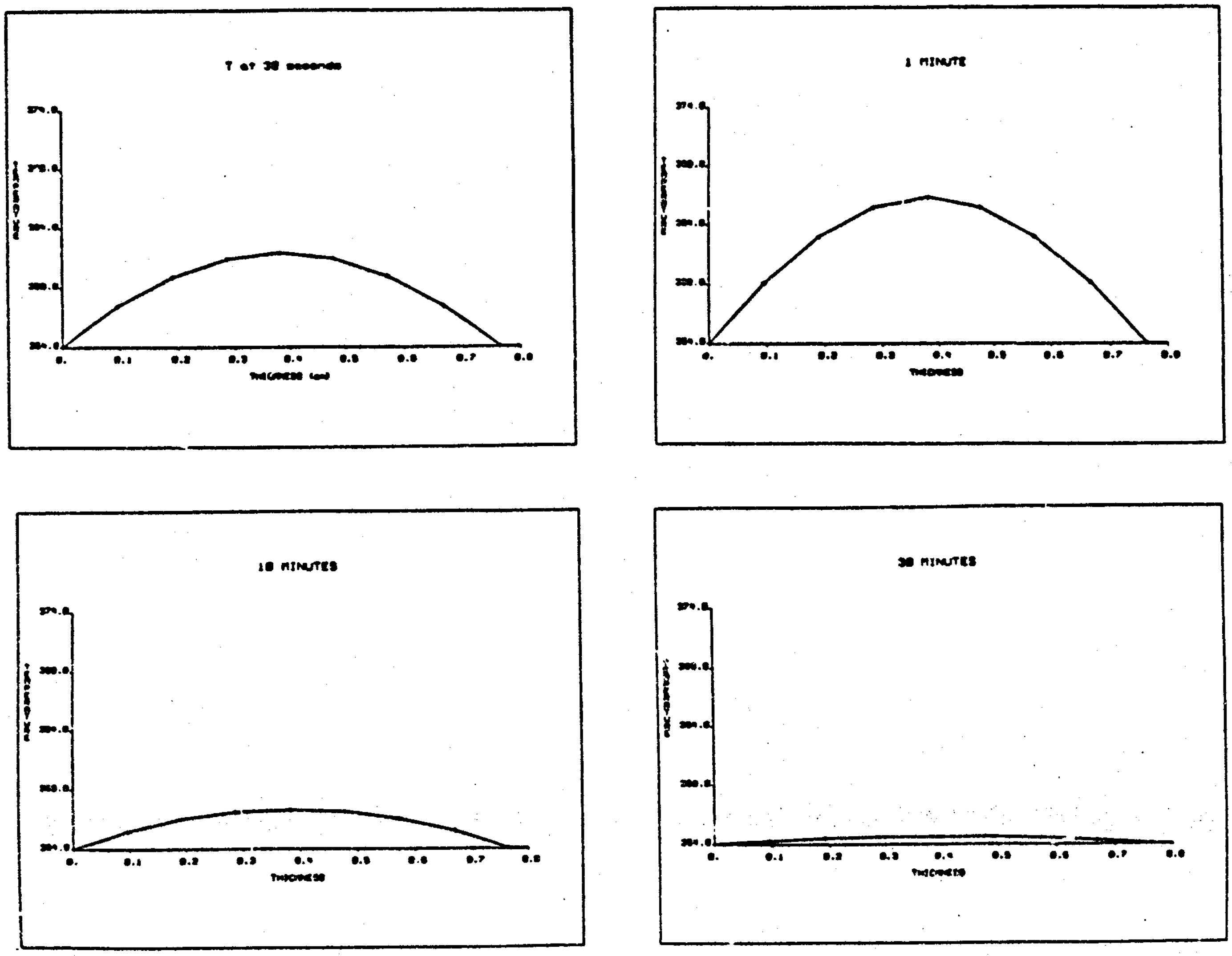
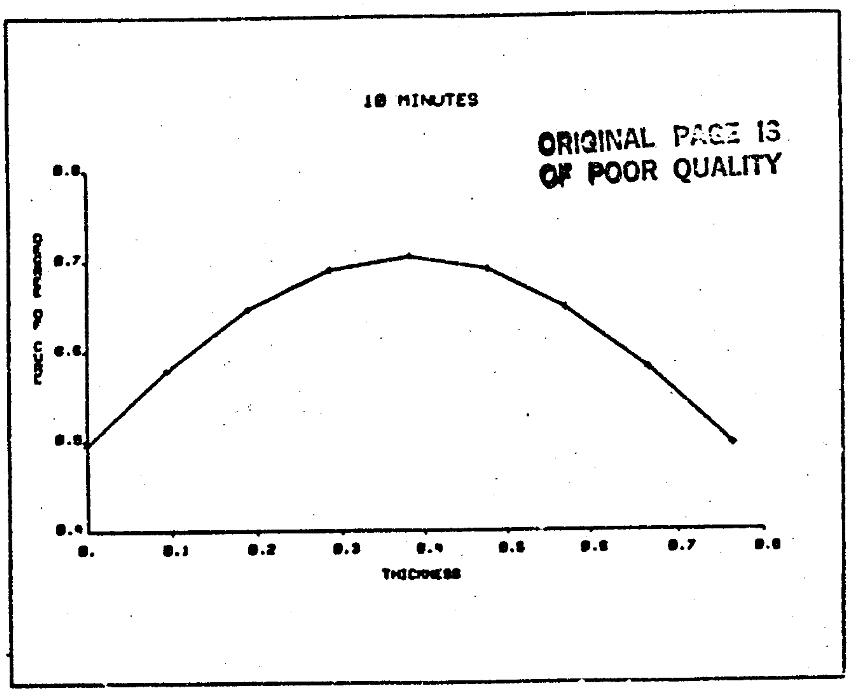


Figure V-B-1. Temperature Distribution Through the Thickness of the Composite at Various Times when Subjected to



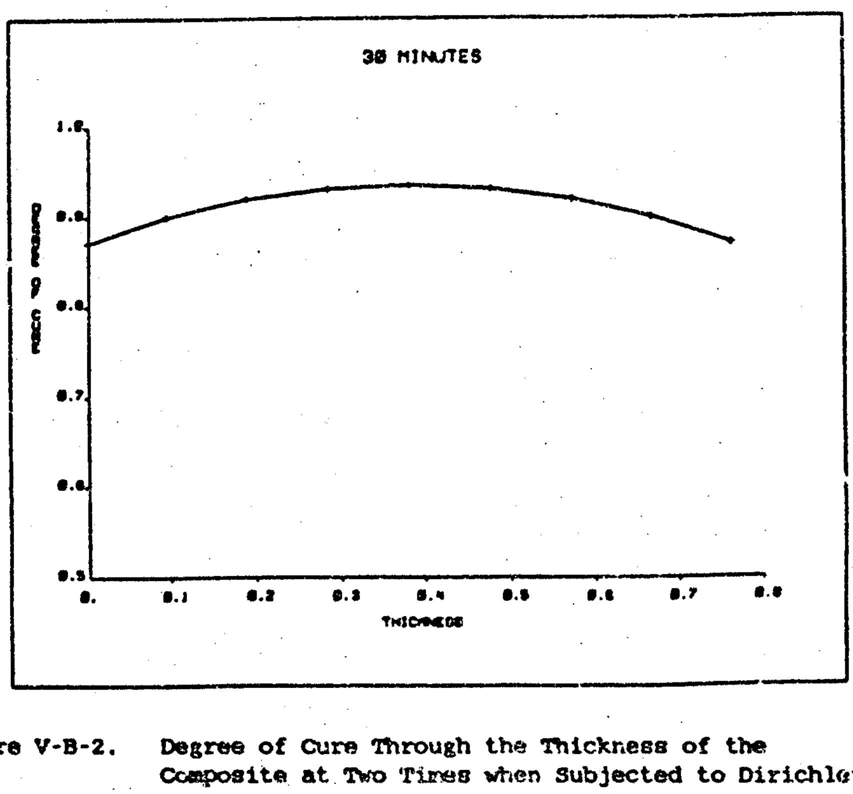


Figure V-B-2. Degree of Cure Through the Thickness of the Composite at Two Times when Subjected to Dirichlet Boundary Conditions.

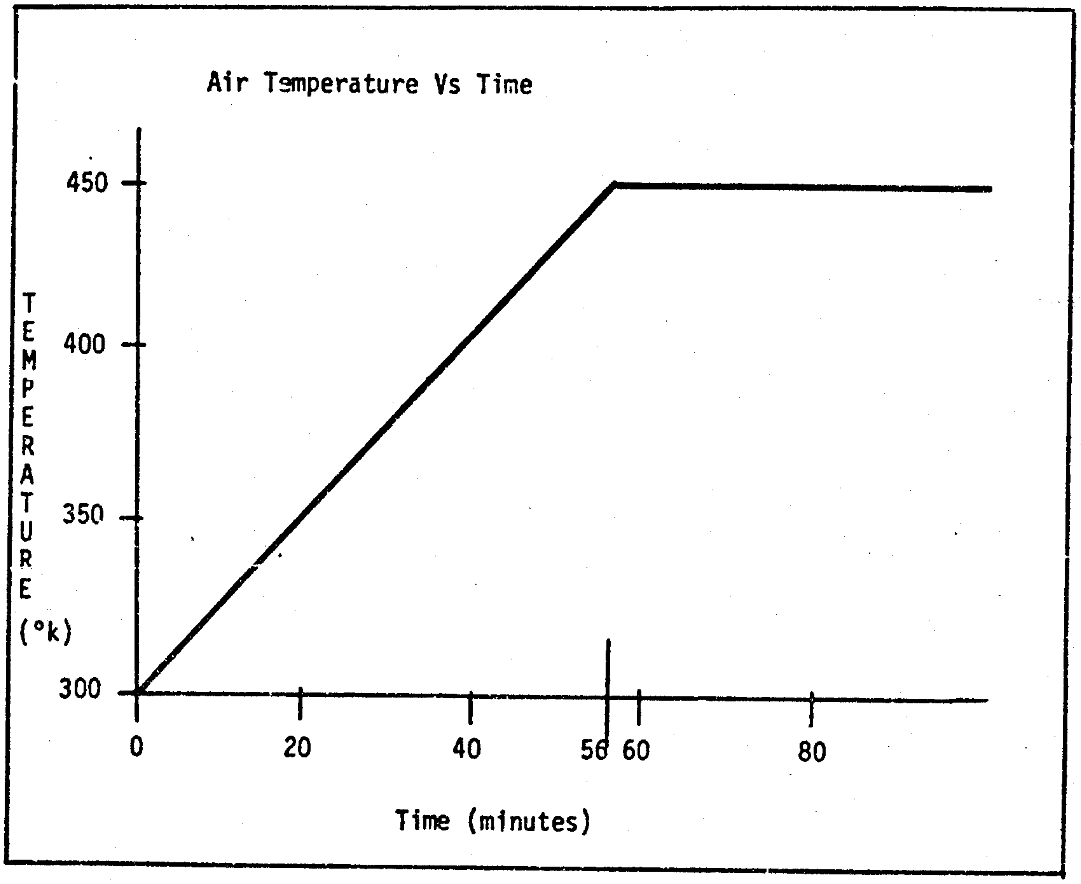


Figure V-B-3. **Air Temperature as a Function of Time for the Composite Subjected to Von Neumann Type Boundary Conditions.**

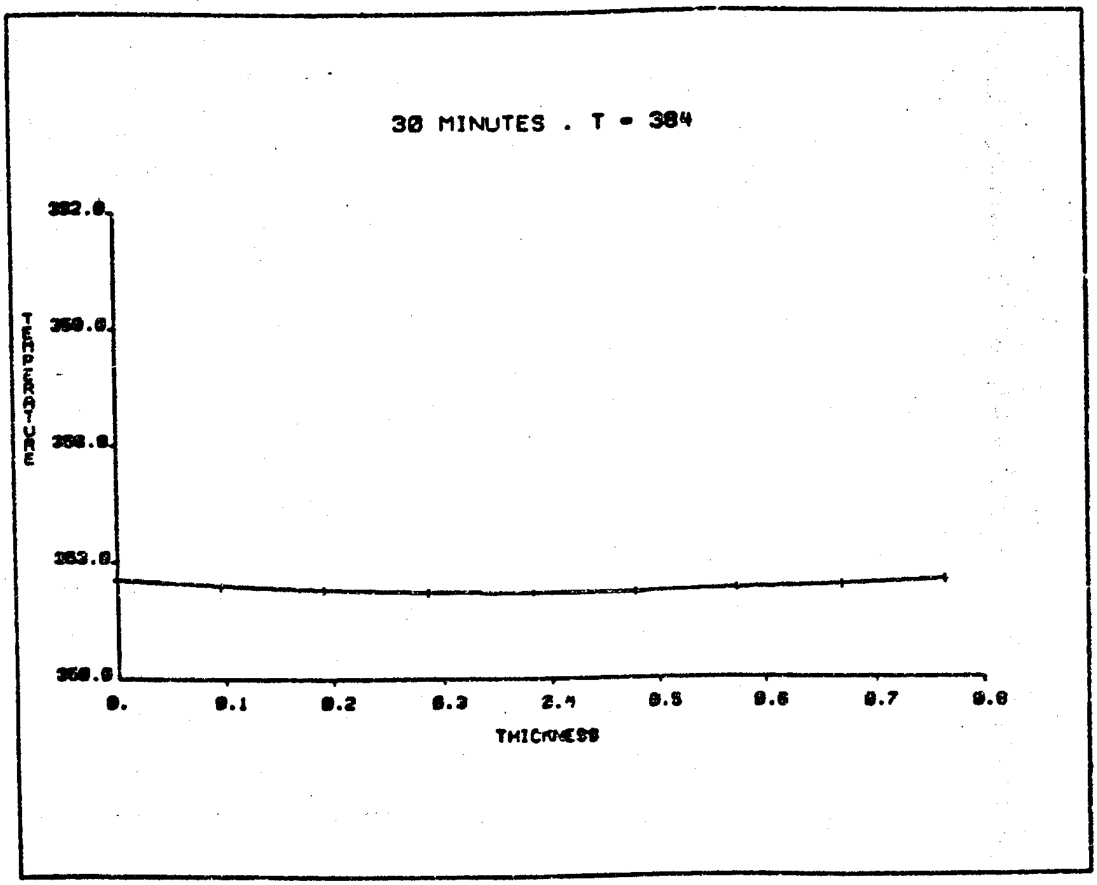


Figure V-B-4. Temperature Distributions Through the Composite at 30 Minutes Into the Cycle at which Time Air Temperature is 384 °K (Neumann Boundary Conditions).

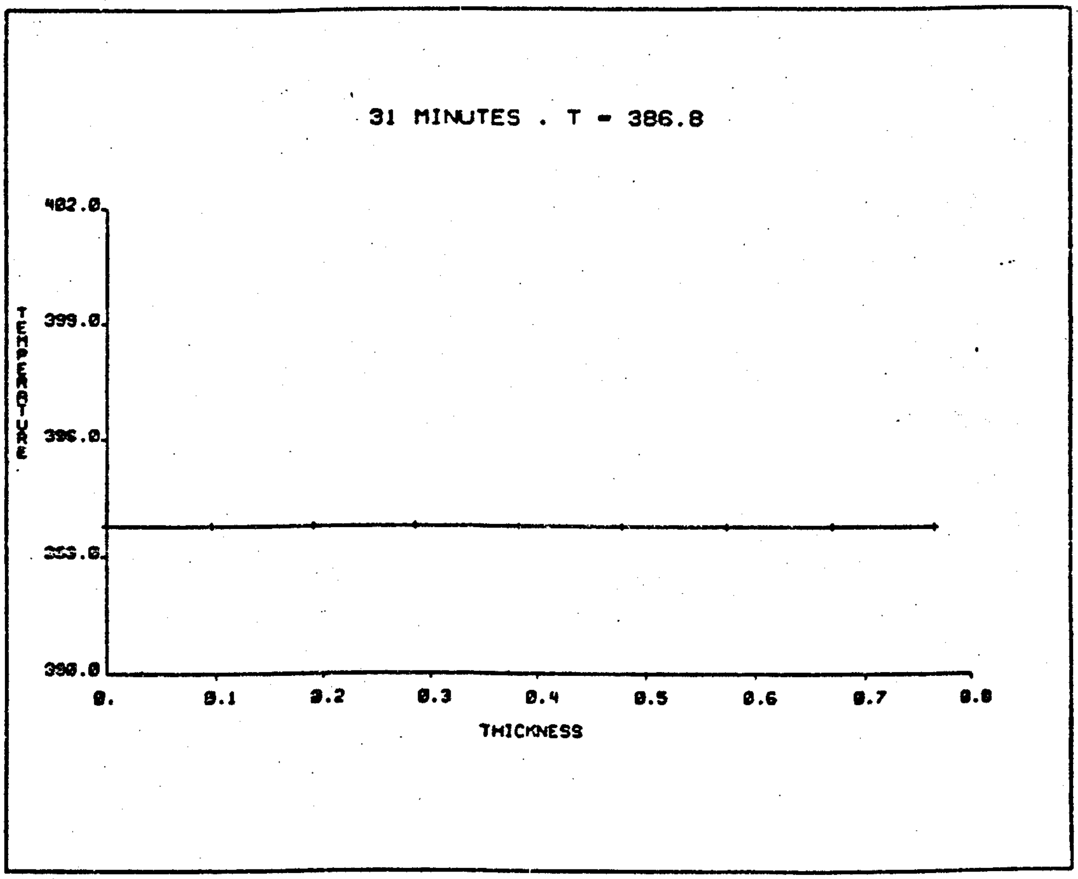


Figure V-B-5. Temperature Distribution Through the Composite at 31 Minutes Into the Cycle at which Time Air Temperature is 386.8 °K (Neumann Boundary Conditions).

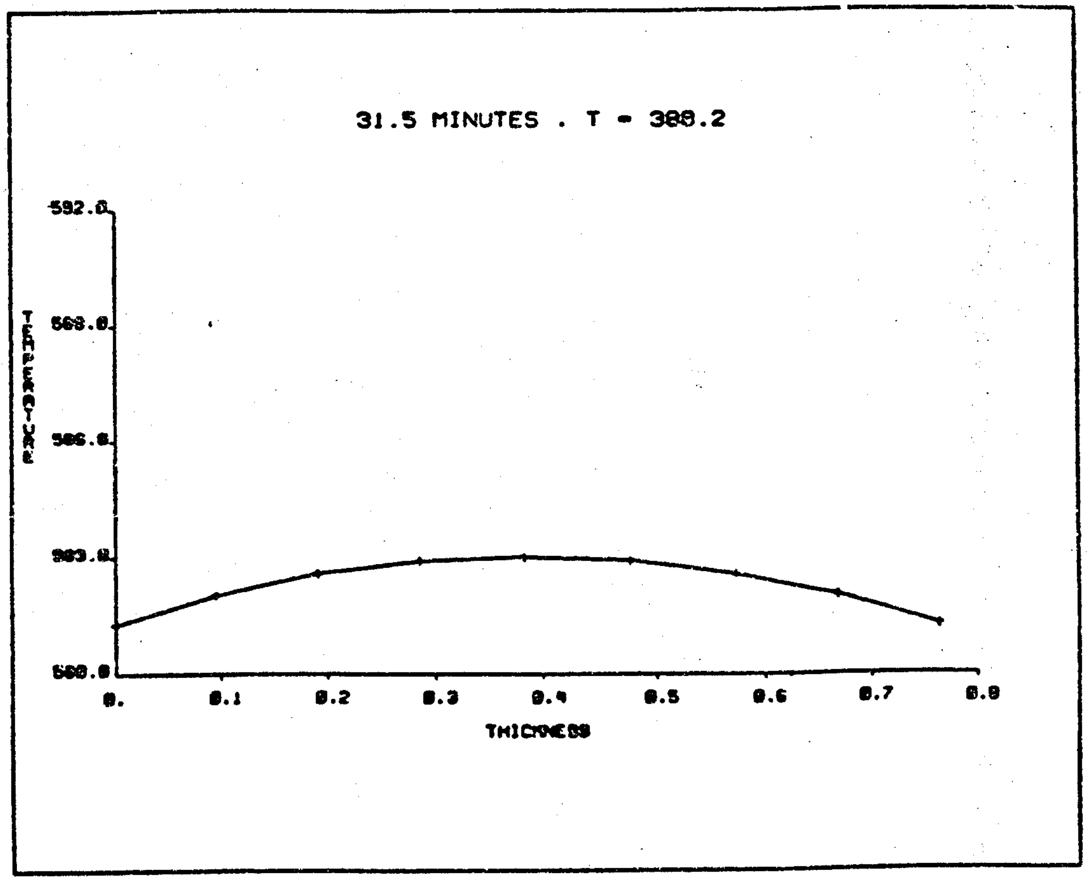


Figure V-B-6. Temperature Distribution Through the Composite at 31.5 Minutes Into the Cycle at which Time Air Temperature is 388.2 °K (Neumann Boundary Conditions).

4. Plans for Upcoming Period

Emphasis will be shifted somewhat because of the opportunity to more closely tie the development of our numerical analysis tools with Professor Sternstein's experimental investigations of the viscoelastic response of thermoplastics. Experimental results will provide the material properties of both neat resin and fibers which are to be used to carry out micro-mechanical analyses of small scale systems. These results, along with other experiments, will allow construction of macro-mechanical properties which will, in turn, be used to model the composite as a homogeneous material. This model can then be used to analyze the specific configurations tested by Professor Sternstein. Numerical results will be compared with experimental results, and once good comparisons are obtained, the detailed stress distribution provided by the finite element results will be combined with the results from experiments to develope failure criteria.

5. References

[1] "Differential Scanning Calorimetry of Epoxy Cure: Isothermal Cure Kinetics"; Sourour, S. and Kamal, M. R., Thermochemica Acta, Vol. 14, 1976

[2] "Curing of Epoxy Matrix Composites"; Journal of Composite Materials, Vol. 17, 1983

[3] Mechanics of Composite Materials; Jones, R. M., McGraw-Hill, 1980

[4] "Thermal Conductivities of Unidirectional Materials"; Journal of Composite Materials, Vol. 1, 1967

6. Current Publications or Presentations by Professor Shephard on this Subject

"Automatic Crack Propagation Tracking"

Presented at the Symposium on Advances & Trends in Structures and Dynamics, Washington, DC, Oct 22-24, 1984. Published in Computers and Structures, Vol. 20, pp. 211-223, 1985.

V-C Heat Treatment of Metal Matrix Composites

Senior Investigator: N. Stoloff

1. Introduction

Directionally solidified eutectics continue to promise superior high temperature strength properties, potentially lower costs and reduced reliance on scarce or imported alloying elements for many aerospace applications. This new project was undertaken to attempt to acheive advances in this field and also to encourage interchange between metal matrix research, on the one hand, and anisotropic resin matrix research, as reviewed in Section II-A-1 of this report, on the other hand.

2. Progress During Report Period

During this reporting period, work was performed on post-solidification heat treatments designed to improve the tensile strength and fatigue resistance of metal-matrix eutectic composites. The alloy system chosen for study is Fe-Mn-Cr-C, which is among the strongest and easiest to grow as a composite of all such alloys identified to date. A variable in this study is the Mn content; with Mn present the matrix is austenitic, with Mn absent, it is ferritic.

Directionally solidified ingots of Fe-30%Cr-3%C were subjected to several solution treatments and aging cycles during this period, as follows:

a. solution treated at 1210 °C, aged at 850 °C
b. solution treated at 1170 °C, aged at 850 °C
c. solution treated at 1210 °C, aged at 925 °C
d. solution treated at 1170 °C, aged at 925 °C

This material was found to be much less responsive to aging than the previously tested Fe-20%Cr-10Mn-3.4C alloy. Aging at 850 °C provided peak hardnesses near 800 VHN for both solution treatment temperatures, while aging at 925 °C provided peak hardnesses between 550 and 575 VHN.

Compression testing was begun on samples of the two test alloys. The Fe-30Cr-3C alloy, tested at room temperature in the as-solidified condition, yielded at 320,000 psi (2208 MPa); Fe-20Cr-10Mn-3.4C, solutionized at 1170 °C for 6 hours and aged at 850 °C for 24 hours exhibited a yield stress of 353,500 psi (2436 MPa). Both alloys failed in a brittle manner at somewhat higher stresses. The measured yield stresses are unusually high, even among high strength composites,

and may reflect a tension-compression anisotropy, as has previously been reported for other eutectics.

3. Current Publications or Presentations by Professor Stoloff on this Subject

"Current Status and Prospects of Eutectic Composite Superalloys"

Presented at the Superalloy Seminar, Chung Shan Institute of Science & Technology, Lung-Tan, China, Dec 14-17, 1984.

V-D Initial Sailplane Project: The RP-1

Senior Investigators: F. P. Bundy,
R. J. Diefendorf,
H. Hagerup

During this reporting period the RP-1 glider has been disassembled and stored on the balcony of the Composite Materials Shop Area in the Jonsson Engineering Center under ambient conditions of temperature and humidity. The instruments and radio have been removed from the aircraft for use in the RP-2 sailplane. During the next reporting period it will be assembled and subjected to its annual load-deflection testing to over 4 G's to check on the degree of its stiffness and strength variability with time.

V-E Second Sailplane Project: The RP-2

Senior Investigators: F. P. Bundy,
R. J. Diefendorf,
H. Hagerup

1. Status

During the previous reporting period the aft wing tension linkage system was built into the torque box of the fuselage and the inboard, aft sections of the wings, and the entire fuselage-wing system was static-tested for all loading conditions successfully. These tests included wing bending, wing torsion, towhook pulls and release under load, landing gear strength, tail boom and empennage strength and stiffness.

2. Progress During Report Period

During the current reporting period effort has been focused on completing the aircraft in preparation for flight tests. These activities, organized as sub-projects, included mounting and attaching the left and right fuselage skins to the fuselage mainframe; fabricating the canopy and its rimframe so as to match the cockpit rimframe; fabricating the instrument panel with its mountings for instruments, radio, tow-cable release, and vent air fixture; completing and streamlining the skid/towhook/landing wheel fairing; fabricating and installing the ventilation air opening, ducting, and control fitting (including the pitot tube at the nose opening); fabrication of a radio battery compartment in the seat back; installation of the seat belt and shoulder harness; etc. At the close of this reporting period the aircraft was approaching the point of final contouring and primer painting, testing for weight and center of gravity adjustment, and readiness for flight testing.

As part of the readiness procedure, an independent calculation of the pitch controllability of the aircraft over the flight envelope range of speeds for a range of center of gravity positions was performed using the measured angle of tailplane chord to wing chord and the lift and moment coefficients for the airfoils involved. It appears that the aircraft should be quite controllable in pitch at a gross weight of 340 pounds if the CG lies within a position range from 0.15 to 0.45 chord aft of the leading edge. The first test flights will be made with the CG at about 0.25 chord aft of the leading edge.

3. Plans for Upcoming Period

During the upcoming period it is expected that the aircraft will be completed, including painting, checked out for critical parameters, then test flown at Saratoga County Airport, first by winch launch, and then by airplane tow. After the ground running and flight handling characteristics are checked out, a series of flights in stable air conditions will be devoted to establishing quantitatively the "polar diagram" of the aircraft.

As reported two periods ago, the RP-2 has a secure covered trailer which will be used to transport it to the airport and to house it safely between tests.

PART VI

TECHNICAL INTERCHANGE

TECHNICAL INTERCHANGE

Technical meetings, both on- and off-campus, enhance opportunities for the interchange of technical information. In order to assure that a Rensselaer faculty/staff member can participate in such meetings off campus, a central listing of upcoming meetings is compiled, maintained and distributed on a quarterly basis. The calender for this reporting period is shown in Table VI-1. Table VI-2 shows the meetings attended by RPI composites program faculty/staff/students during the reporting period. Some on-campus meetings, with special speakers particularly relevant to composites, are listed in Table VI-3. A list of composites-related visits to relevant organizations, attended by RPI faculty/staff/students, along with the purpose of each visit is presented in Table VI-4.

The diversity of the research conducted within this program has continued to be wide; indeed, it is seen as one of the strengths of the program. To insure information transfer among groups on campus, a once-a-week luncheon program is conducted. Faculty and graduate students involved (listed in Part VII - Personnel - of this report) attend. These meetings are held during the academic year and are known as "Brown Bag Lunches" (BBL's), since attendees bring their own. Each BBL allows an opportunity for graduate students and faculty to briefly present plans for, problems encountered in and recent results from their individual projects. These seminars also are occasions for brief reports on the content of off-campus meetings attended by any of the faculty/staff participants (as listed in Tables VI-2 and VI-4 of this report) and for brief administrative reports, usually on the part of one of the Co-Principal Investigators. Off-campus visitors, at RPI during a BBL day, are often invited to "sit in". Table VI-5 lists a calender of internal, oral progress reports as they were given at BBL's during this reporting period.

As indicated in the Introduction of this report, an initiative is being implemented which has, over this and the previous reporting period, brought about increased communication between NASA researchers and their RPI counterparts. One step in that direction has been taken by the holding of a series of Research Coordination Meetings. The first of such meetings was held at RPI during the last reporting period and 14 members of RPI's Composite Materials and Structures Program along with 7 members of NASA Langley Research Center's Materials Division were present. A second meeting took place on February 25, 1985 at R.P.I. with 12 members of R.P.I.'s Composite Materials and Structures Program and 11 members

from NASA Lewis Research Center. A list of this as well as other interactions which took place during the reporting period is given in Table VI-6.

Table VI-1

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Calendar of Composites-related Events

September 30, 1984 through April 30, 1985

DATES	MEETING	SPONSOR	PLACE
02-04 Oct 84	Fourth Annual Metallic Structures MMC Review	AFWAL/FIBA WPAFB,OH	Thousand Oaks, CA
02-05 Oct 84	ASNT Fall Conf. & Display	ASNT	Cincinnati, OH
09-11 Oct 84	16th National SAMPE Technical Conference	SAMPE	Albuquerque, NM
15-17 Oct 84	10th Ann. Mech. of Comp. Structures & Dynamics	USAF/U. DAYTON	Dayton, OH
16-18 Oct 84	AHS Specialists' Mtg on Fatigue Methodology	AHS	St. Louis, MO
17-19 Oct 84	7th DOD/NASA Conf. on Fiber Composites in Structural Design	DOD/NASA	Dayton, OH
22-25 Oct 84	Symp. on Adv. & Trends in Structures & Dynamics	AIAA/NASA	Washington, DC
24-25 Oct 84	Symposium on Composites: Fatigue and Fracture	ASTM	Dallas/Ft. Worth, TX
13-15 Nov 84	Conf. on Processing of Metal & Ceramic Matrix Composites	MCIC/MMCIAC	Columbus, OH
27-29 Nov 84	Weapon Sys. Readiness - Airframe Mngment Role	USAF	Macon, GA
04-07 Dec 84	Italian Assoc. for Thermal Analysis and Calorimetry Mtg	IATAC	Naples, Italy
09-14 Dec 84	ASME Winter Annual Mtg	ASME	New Orleans, LA
17-18 Dec 84	Superalloy Seminar	Chung Shan Inst of Sci & Technology	Lung-Tan, China
07-10 Jan 85	Congress on Composites in Manufacturing	SME	Anaheim, CA
20-24 Jan 85	9th Annual Conf. on Composites & Adv. Ceramics	ACS	Cocoa Beach, FL

Table VI-1 *(continued)*

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Calendar of Composites-ielated Events

September 30, 1984 through April 30, 1985

DATES	MEETING	SPONSOR	PLACE
21-23 Jan 85	Seminar: Exper Mech of Fiber Reinforced Comp Matls	SEM(SESA)	Detriot, MI
05-06 Feb 85	Topical Review on Mechanics, Aeronautics, & Propulsion	DOD	Washington, DC
11-14 Feb 85	Conf. on Characterization & Analysis of Polymers	IUPAC	Melbourne, Aust.
12-14 Feb 85	AIAA Aerospace Engr. Show	AIAA	Los Angeles, CA
19-21 Feb 85	Inter. Conf. on Rotor-craft Basic Research	ARO/AHS	Research Triangle Park, NC
xx-xx Feb 85	Asilomar Conference on Polymers	-	Asilomar, CA
11-14 Mar 85	Design Engineering Conf.	ASME	Chicago, IL
13-15 Mar 85	Symp. on Toughened Comp.	ASTM/NASA-LRC	Houston, TX
18-1^ Mar 85	Symp. on Fatigue in Mech. Fastened Comp. & Mtl. Joints	ASTM	Charleston, SC
19-21 Mar 85	30th National SAMPE Symposium/Exposition	SAMPE	Anaheim, CA
25-29 Mar 85	American Physical Society Mtg	APS	Baltimore, MD
25-29 Mar 85	International Conf. on Robotics & Automation	IEEE(C)	St. Louis, MO
01-02 Apr 85	IEEE(IA) Tech. Conf. on Rubber and Plastics	IEEE	Akron, OH
01-04 Apr 85	6th Conf. on Deformation Yield & Fracture of Polymers	PRI	Cambridge, Englnd
09-11 Apr 85	AIAA Annual Mtg	AIAA	Washington, DC
09-12 Apr 85	Comuter Integrated Manu-facturing Industry Conf.	USAF	Dallas, TX

Table VI-1 *(continued)*

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Calendar of Composites-related Events

September 30, 1984 through April 30, 1985

DATES	MEETING	SPONSOR	PLACE
14-18 Apr 85	Inter. Conf. on Wear of Materials	AIME/ASME/ASTM/ ASM/ACerS/ASLE	Vancouver, BC, Canada
15-17 Apr 85	26th Structures, Struct. Dyn. & Matls. Conf.	AIAA/ASME/ASCE/ AHS	Orlando, FL
16-17 Apr 85	Defects in Comp.: Detect. & Significance	Imperial Coll/ RAE	London, England
16-18 Apr 85	40th Symp. on Mechanical Failures Prevention	NBS	Gaithersburg, MD
21-26 Apr 85	60th Struct. & Matl. Pnl Mtg.: Damage Tolerance Concepts for Crit. Eng. Comp.	AGARD	SanAntonio, TX
28 Apr-03 May 85	ACS 189th National Mtg	ACS	Miami Beach, FL

Table VI-2

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Pertinent Professional Meetings Attended

September 30, 1984 through April 30, 1985

DATES	MEETING
22-24 Oct 84	Symp. on Adv. & Trends in Structures & Dynamics (Prof. Shephard), Washington, DC Professor Shephard presented the paper: "Automatic Crack Propagation Tracking"
24-25 Oct 84	Symposium on Composites: Fatigue and Fracture (Prof. Krempl), Dallas/Ft. Worth, TX Professor Krempl presented the paper: "Time-Dependent Deformation and Fatigue Behavior of [±55] Graphite/Epoxy Tubes under Combined Loading"
04-07 Dec 84	Italian Assoc. for Thermal Analysis and Calorimetry Mtg (Prof. Wunderlich), Naples, Italy Professor Wunderlich gave the Plenary Lecture: "Precision Heat Capacity Measurements for the Characterization of Two-Phase Polymers"
09-14 Dec 84	ASME Winter Annual Mtg: Advances in Aerospace Sciences and Engineering Symposium (Prof. Sham), New Orleans, LA
17-18 Dec 84	Superalloy Seminar, Chung Shan Inst of Sci & Technology (Prof. Stoloff), Lung-Tan, China Professor Stoloff presented the paper: "Current Status and Prospects of Eutectic Composite Superalloys"
XX-XX Feb 85	Asilomar Conference on Polymers (Prof. Sternstein), Asilomar, CA Professor Sternstein presented the paper: "Mechanical Characterization of Composites"
25-29 Mar 85	American Physical Society Mtg (Prof. Wunderlich), Baltimore, MD Professor Wunderlich presented the papers: "The Kinetics of Molecular Nucleation", with Dr. S. Cheng "Thermal Analysis of the Condis Crystals of Poly-p-xylylene"

Table VI-2 *(continued)*

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Pertinent Professional Meetings Attended

September 30, 1984 through April 30, 1985

DATES	MEETING
01-04 Apr 85	6th Conf. on Deformation Yield & Fracture of Polymers (Prof. Sternstein), Cambridge, England Professor Sternstein presented the paper: "Deformation and Failure of Thermoplastic Matrix Composites"
21-26 Apr 85	60th AGARD Structures & Materials Panel Mtg.: Damage Tolerance Concepts for Critical Engine Components (Prof. Loewy), San Antonio, TX
28-Apr-03 May 85	ACS 189th National Mtg (Prof. Sternstein/Prof. Wunderlich), Miami Beach, FL Professor Sternstein presented the paper: "Mechanical and Optical Characterization of Thermoplastic Matrix Composites" Professor Wunderlich presented the Invited Plenary Lecture: "Thermal Analysis of Liquid and Condis Crystals"

Table VI-3

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Composites-Related Meetings/Talks Held at RPI

September 30, 1984 through April 30, 1985

SUBJECT	SPEAKER	DATE
Phase Transformations in Solids	Prof. R. D. James Brown University Providence, RI	10/29/84
Finite Element Approach in Dynamics	Prof. M. Borri Politecnico Di Milano Milan, Italy	10/31/84
Advanced Composite Applications at McDonnell Aircraft	Howard Siegel Director, Product Engrg McDonnell Aircraft Company	2/12/85
Design of Composite Structures	Daniel S. Adams Hercules Aerospace	2/18/85
R & D Activities at Hughes Helicopters	R. Prouty & J. Schibler Hughes Helicopters Culver City, CA & Mesa, AZ	2/25-26/85
Interlaminar Fracture Toughness of Composite Structures	Prof. L. Rehfield Georgia Institute of Technology	3/26/85
Review of Structures, Dynamics & Materials Aspects of RTC Prgm	Dr. Gary Anderson ARO Durham, NC	3/27/85
Damage Zone Modeling of Notched Composites Under Tension	Prof. J. Bäcklund Royal Inst of Technology Stockholm, Sweden	4/17/85

Table VI-4

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Composites-Related Visits to Relevant Organizations

September 30, 1984 through April 30, 1985

Faculty Member	Purpose of Visit	Location	Date(s)
O. Bauchau	Discussion of Thin-Walled Structures	Langley Visit, with M. Nemeth	11/26/84
B. Wunderlich	Presented Inv Lecture: "Transitions in Mesophases of Macromolecules"	Polymer Forum DuPont Co., Wilmington, DE	1/10/85
J. Diefendorf	Discussion & Seminar Carbon/Carbon Composites	Langley Visit, with R. Maas	2/7/85
B. Wunderlich	Presented Inv Lecture: "The Physical Chemistry of Polyethylene"	Mobil Chemical Co, Edison, NJ	2/20/85
S. Sham	Discussion of NASA Facilities & Fracture of MMC & Gr/E	Langley Visit, with W. Elber, W. Johns, J. Newman, K. O'Brien, C. Poe	3/22/85
S. Sham	Discussion of Gr/E & MMC Models & Ceramic Systems	Lewis Visit, with C. Chamis, J. DiCarlo	3/28/85
M. Shephard	Presented seminar: "Toward the Automation of Finite Element Modeling"	Purdue U. Lafayette, IN	3/28/85
R. Loewy	Discussion of NDE Techniques	Southwest Research Institute, San Antonio, TX, with H. N. Abramson, M. Goland	4/23/85
M. Shephard	Presented seminar: "Discrete Crack Propagation Tracking with Automated Finite Element Modeling Techniques"	Cntr for Comp. Matls, U. of Delaware, Newark, DE	4/24/85

Table VI-5

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Brown Bag Lunch Schedule

September 30, 1984 through April 30, 1985

DATE	TOPIC	RESP. FACULTY
05-Oct	Administrative Report	Wiberley
	Resin Matrix Characterization	Sternstein
	Stress Concentration Failure Criteria	Goetschel
12-Oct	Administrative Report	Diefendorf
	Curing Uniformity	Wunderlich
	Numerical Analysis of Comp. Processing	Shephard
19-Oct	Administrative Report	Wiberley
	Composites Fatigue	Krempl
	Ordered Polymers	Diefendorf
26-Oct	Administrative Report	Diefendorf
	Edge Failures	Sham
	Fabrication Technology	Bundy/Hagerup/Paedelt
02-Nov	Administrative Report	Loewy
	Eutectics	N. Stoloff
	Beams with Warping	Bauchau
09-Nov	Administrative R[illegible]t	Wiberley
	Resin Matrix C[illegible]ization	Sternstein
	Numerical Anal[illegible] of Comp. Processing	Shephard
16-Nov	Administrative Report	Loewy
	Curing Uniformity	Wunderlich
	Stress Concentration Failure Criteria	Goetschel
23-Nov	Thanksgiving Recess	
30-Nov	Administrative Report	Diefendorf
	Composites Fatigue	Krempl
	Ordered Polymers	J. Diefendorf
07-Dec	Administrative Report	Loewy
	Edge Failures	Sham
	Beams with Warping	O. Bauchau
14-Dec	Administrative Report	Diefendorf
	Numerical Analysis of Comp. Processing	Shephard
	Fabrication Technology	Bundy/Hagerup/Paedelt
18-Jan	Administrative Report	Loewy
	Eutectics	Stoloff
	Ordered Polymers	Diefendorf

Table VI-5 *(continued)*

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Brown Bag Lunch Schedule

September 30, 1984 through April 30, 1985

DATE	TOPIC	RESP. FACULTY
25-Jan	Administrative Report	Loewy
	Beams with Warping	Bauchau
	Composites Fatigue	Krempl
01-Feb	Administrative Report	Loewy
	Resin Matrix Charactization	Sternstein
	Curing Uniformity	Wunderlich
08-Feb	Administrative Report	Wunderlich
	Edge Failures	Shaw
	Numerical Analysis of Comp. Processing	Shephard
15-Feb	Administrative Report	Diefendorf
	Fabrication Technology	Bundy
		Hagerup
		Paedelt
	Eutectics	Stoloff
22-Feb	Administrative Report	Loewy
	Ordered Polymers	Diefendorf
	Beams with Warping	Bauchau
	VISITORS: A. Bakke, Hercules Aerospace	
	Dr. S. Wagner, U. of A.F.,	
	Dr. U. Leiss F.R.G.	
	Dr. J. Yin, Bell Helicopters	
01-Mar	Administrative Report	Loewy
	Composites Fatigue	Krempl
	Resin Matrix Charactization	Sternstein
08-Mar	Administrative Report	Diefendorf
	Curing Uniformity	Wunderlich
	Edge Failures	Shaw
15-Mar	Spring Recess	
22-Mar	Administrative Report	Loewy
	Numerical Analysis of Comp. Processing	Shephard
	Fabrication Technology	Bundy
		Hagerup
		Paedelt
29-Mar	Administrative Report	Diefendorf
	Discussion Session - "Where do we want the program to be in 5 years?"	

Table VI-5 *(continued)*

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Brown Bag Lunch Schedule

September 30, 1984 through April 30, 1985

DATE	TOPIC	RESP. FACULTY
05-Apr	Administrative Report	Diefendorf
	Beams with Warping	Bauchau
	Composites Fatigue	Krempl
12-Apr	Administrative Report	Diefendorf
	Curing Uniformity	Wunderlich
	Edge Failures	Sham
19-Apr	Administrative Report	Loewy
	Resin Matrix Charactization	Sternstein
	Numerical Analysis of Comp. Processing	Shephard
26-Apr	Administrative Report	Diefendorf
	Fabrication Technology	Bundy
		Hagerup
		Paedelt
	Eutectics	Stoloff

Table VI-6

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Review of Research Center Interactions

September 30, 1984 through April 30, 1985

Faculty Member(s)	Purpose	Nature of Interchange	Date(s)
D. Goetschel (Gilbert Hu)	Test Program on Strength of Notched Composite Laminates	Correspondence, with Dr. M. Shuart, Langley RC	11/16/84
O. Bauchau	Discussion of Thin-Walled Structures	Langley Visit, with M. Nemeth, Langley RC	11/26/84
E. Krempl	Consideration of Tubular Fatigue Specimen Testing	Correspondence, with Dr. Wolf Elber, Langley RC	12/26/84 EK to WE
E. Krempl	Consideration of Tubular Fatigue Specimen Testing	Correspondence, with Dr. Wolf Elber, Langley RC	1/7/85 WE to EK
E. Krempl	Consideration of Tubular Fatigue Specimen Testing	Correspondence, with Dr. Wolf Elber, Langley RC	3/4/85 EK to WE
J. Diefendorf	Discussion & Seminar Carbon/Carbon Composites	Langley Visit with R. Maxw	2/7/85
O. Bauchau J. Diefendorf G. Dvorak E. Krempl R. Loewy V. Paedelt S. Sham M. Shephard S. Sternstein S. Stoloff B. Wunderlich	Research Coordination Meeting, Lewis RC	Campus Visit, by K. Bowles C. Chamis J. DiCarlo B. Johns S. Levine B. Probst G. Roberts T. Serafini R. Vanucci	2/25/85
S. Sham	Discussion of NASA Facilities & Fracture of MMC & Gr/E	Langley Visit, with W. Elber W. Johns J. Newman K. O'Brien C. Poe	3/22/85

Table VI-6 *(continued)*

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Review of Research Center Interactions

September 30, 1984 through April 30, 1985

Faculty Member(s)	Purpose	Nature of Interchange	Date(s)
S. Sham	Discussion of Gr/E & MMC Models & Ceramic Systems	Lewis Visit, with C. Chamis J. DiCarlo	3/28/85

PART VII

PERSONNEL, AUTHOR INDEX

PERSONNEL

<u>Co-Principal Investigators</u>

Loewy, Robert G., Ph.D.	Institute Professor
Wiberley, Stephen E., Ph.D.	Professor of Chemistry

<u>Senior Investigators</u>

Bauchau, O., Ph.D. (Structural dynamics, advanced composites)*	Assistant Professor of Aeronautical Engineering
Bundy, F. P., Ph.D. (Physical chemistry, structures testing)*	Research Professor of Materials Engineering
Diefendorf†, R. J., Ph.D. (Fabrication, resin matrix, fiber behavior, interfaces)*	Professor of Materials Engineering
Feeser†, L. J., Ph.D. (Computer applications & graphics, computer-aided-design, optimization)*	Professor of Civil Engineering Associate Dean, School of Engineering
Goetschel, D. B., Ph.D. (Structural analysis, design and testing)*	Assistant Professor of Mechanical Engineering
Hagerup, H. J., Ph.D. (Aerodynamics, configuration, pilot accomodation, flight testing)*	Associate Professor of Aeronautical Engineering
Krempl, E., Dr.Ing. (Fatigue studies, failure criteria)*	Professor of Mechanics and Director of Cyclic Strain Laboratory
Sham, T.-L., Ph.D. (Fracture mechanics, composites)*	Assistant Professor of Mechanical Engineering
Shephard, M. S., Ph.D. (Computer graphics, finite element methods)*	Associate Professor of Civil Engineering and Associate Director, Center for Interactive Computer Graphics
Sternstein†, S. S., Ph.D. (Failure analysis, matrix behavior, moisture effects)*	William Weightman Walker Professor of Polymer Engineering

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* Fields of Specialty

† Member of Budget Committee together with Co-Principal Investigators

Stoloff, N. S., Ph.D. — Professor of Materials Engineering
(Mechanical behavior of crystals, order-disorder reactions, fracture, stress corrosion)*

Wunderlich, B., Ph.D. — Professor of Chemistry
(Processing science, constituent material characteristics)*

Research Staff

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Paedelt, Volker

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Srinivasan, Krishna, B.Tech.
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Kirker, Philip
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O'Connell, James
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Spyropoulos, Constantine
Van Roggen, Edgar
Young, Richard

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* Fields of Specialty

† Member of Budget Committee together with Co-Principal Investigators

<u>Undergraduate Assistants - Sophmores</u>

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Dawkins, Wilbert
Femino, John
Jacob, Daniel
Karkow, Jon
Meyer, John
Park, Brian
Pusateri, Robert
Rosario, Estrella

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